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New reagents for radical allylations, and the synthetic use of 5-*endo* trigonal radical cyclization

by

Zhongren Wang

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science.

Department of Chemistry

Edmonton, Alberta

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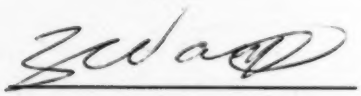

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Dr. M. Cowie

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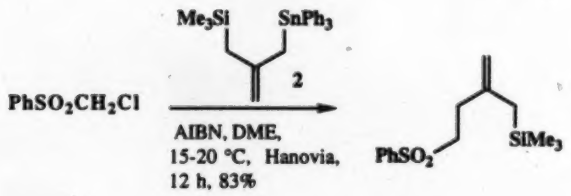
Dr. F. Jamali

Date: April 23, 1997

To my parents, my wife, and my son.

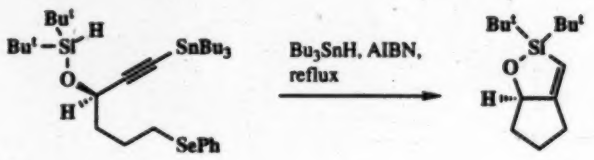
ABSTRACT

The first chapter of this thesis describes research that shows that trimethyl[2-[(tributylstannyl)methyl]-2-propenyl]silane (**1**) and trimethyl[2-[(triphenylstannyl)methyl]-2-propenyl]silane (**2**), both of which are easily prepared, can be used for photochemically-induced radical allylation of alkyl halides. The products are allylic silanes (eq. 1). The reagents work best with electron-deficient radicals, such as those carrying an adjacent carbonyl (ketone or ester) or sulfonyl group.



Eq. 1

The second chapter of this thesis describes studies on Baldwin-Beckwith disfavored 5-*endo*-trig radical cyclizations. Several cyclization precursors have been made, and cyclized by a radical process involving a sequence of 5-*exo*-dig ring closure, intramolecular 1,5-hydrogen transfer, 5-*endo*-trig cyclization, and tin extrusion. The products are vinylsilanes (eq. 2). Some of the products are five- and six-membered heterocycles containing oxygen or nitrogen. The results show that substituted tetrahydrofuran, pyrrolidine and chromanol systems are accessible by this type of radical cyclization process.



Eq. 2

ACKNOWLEDGMENTS

I would like to express my sincerest gratitude to my supervisor, dear Professor Derrick L. J. Clive, for his advice, encouragement and support during my entire graduate program, and for his assistance in the preparation of this thesis.

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LIST OF ABBREVIATIONS

ABCC	1,1'-azobis(cyclohexanecarbonitrile)
Ac	acetyl
AIBN	2,2'-azobisisobutyronitrile
BOC	*tert*-butoxycarbonyl
Bn	benzyl
Bu	butyl
Bu^t	*tert*-butyl
DBU	1,8-diazabicyclo[5.4.0]undec-7-ene
DIBAL-H	diisobutylaluminum hydride
DME	1,2-dimethoxyethane
DTBP	di-*tert*-butylperoxide
Et	ethyl
GC	gas chromatography
h	hours
HMPA	hexamethylphosphoric triamide
LDA	lithium diisopropylamide
Me	methyl
MOM	methoxymethyl
Ms	methanesulfonyl
Ph	phenyl
PhH	benzene
TBAF	tetrabutylammonium fluoride
THF	tetrahydrofuran
TMEDA	tetramethylethylenediamine
TMS	trimethylsilyl
p-TSA	*p*-toluenesulfonic acid

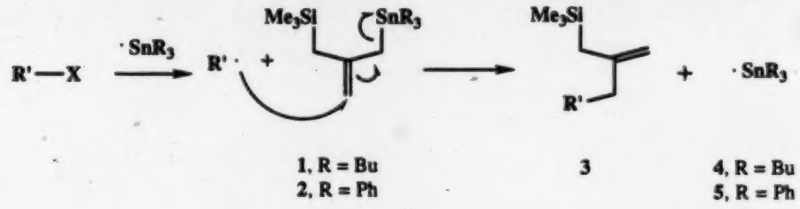
CHAPTER 1

Radical Allylations with Trimethyl[2-[(tributylstannyl)methyl]-2-propenyl]silane or Trimethyl[2-[(triphenylstannyl)methyl]-2-propenyl]silane

I. INTRODUCTION

The chemistry of allylsilanes has become very extensive since the pioneering works of Sommer,[1] Calas,[2] Corriu,[3] Sakurai,[4] and Fleming.[5] Recently, an extensive review has been written on the subject of silanes,[6] and about a third of this review is devoted solely to the subject of allylsilanes, in particular, the synthetic utility of this structural unit in natural product synthesis.

Alongside the increasing interest in the synthetic usefulness of allylsilanes is a growth in the demand for various ways of introducing an allylic silane moiety into a molecule.[7] For this reason we decided to embark on a novel way of making allylsilanes by a free radical chain process. In particular, we chose to employ trimethyl[2-[(tributylstannyl)methyl]-2-propenyl]silane (**1**) and trimethyl[2-[(triphenylstannyl)methyl]-2-propenyl]silane (**2**). Reagent **1** had been reported recently in the literature, but its synthetic utility has not been explored;[8] reagent **2** has not been reported to the best of our knowledge. Our main strategy (Scheme I-1) involves the



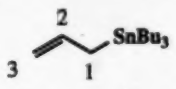
Scheme I-1

generation of a radical **R'·** from **R'-X**, which we anticipated to add to the unsubstituted end of allylic silane-stannane **1** or **2**, to afford the allylsilane **3**, as well as releasing a radical **4** or **5**, respectively. The latter could, in principle, propagate the chain. The reaction we proposed to study involves intermolecular free radical allylation with an allylstannane, and the following is a brief literature survey on intermolecular free radical allylations with allylstannanes.

Radical allylation with allyltributylstannane (eq. 1) is a well-established and synthetically important reaction.[9] Much attention has been focused on the applications in natural products chemistry, including synthesis of nucleosides,[10] α-amino acids,[11] prostaglandins,[12] β-lactams,[13] pseudomonic acid,[14] and compactin.[15]

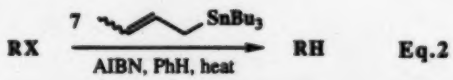
Eq. 1

For the above type of radical allylation (eq. 1), various radical sources are suitable, such as PhS,[16,17] PhSe,[16,17] XC(S)O,[16] PhOC(S)O,[10a,b,g] and halogen,[10g,17,18] and the reaction can be done both by thermal or photochemical procedures. In the case of allylstannane **6**, the tin unit, besides Bu_3Sn, can also be



6

Ph_3Sn,[19] Me_3Sn,[20] $SnCl_2Br$,[21] or $Sn[N(TMS)_2]_2Br$,[22] and much work has been done to identify what substituents can be tolerated on the allyl unit. Alkyl substitution at C(1) or C(3) does not appear to be synthetically useful[23] - at least as a general rule - because of facile 1,3-tin migration,[24] and the fact that crotylstannanes are good hydrogen donors, so that, instead of being allylated, the initial radical is reduced (eq. 2).[16,25]



Eq.2

Oxygen substituents at C(1) of **6** have also been examined; intramolecular processes with AcO at C(1) are successful,[26] but intermolecular reactions when the C(1) substituent is $MeOCH_2O$ do not work.[19] It would seem that, besides the parent compound **6**, only C(2)-substituted allyl stannanes are of general synthetic utility[27] for radical allylation. In these compounds, of course, 1,3-stannane migration is

degenerate. However, for purposes of our discussion, it is more helpful to classify C(2) substituted allylstannanes according to the electronic nature of the substituent. The following classification of C(2) substituted allylstannanes (Tables I-1, I-2, I-3) is based on whether the substituent is (a) electron-withdrawing, (b) a hydrogen, or (c) another group. All the available data have been collected and comparisons will be made within and between the various classes listed in Tables I-1 to I-3.

Table I-1 Electron-withdrawing group at C(2)

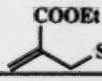
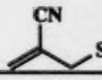
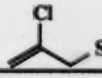
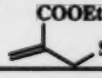
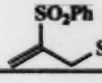
No.	Compound	Reference
11		33, 39
12		19
16		33
17		33
39		21
41		40
42		22

Table I-2 C(2) unsubstituted allylstannanes

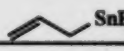
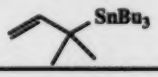
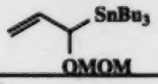
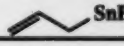
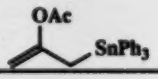
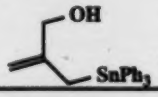
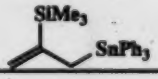
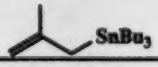
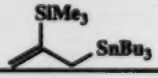
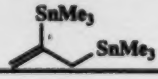
No.	Compound	Reference
6		9, 36
7		32
8		19
9		19
18		19

Table I-3 Miscellaneous C(2) substituents

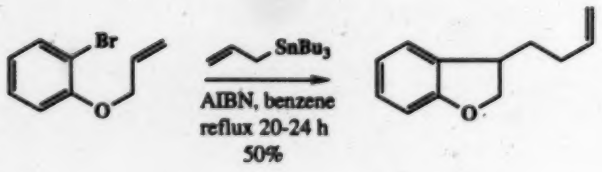
No.	Compound	Reference
10		19
20		34
22		35
26		36
27		36
34		20

In the following short review, it is important to bear in mind that many factors, not just the nature of the C(2) substituent, affect the success of free radical allylations. For instance, the method of radical initiation, the solvent system, the temperature, the presence or absence of radical scavengers, and the nature of the attacking radical itself all affect the course of a free radical chain reaction, so that the outcome depends on a harmonious interplay of a large number of factors.

The simplest and earliest radical allylating agent to be developed was allyltributylstannane (**6**). Reported independently by a French[28] and a Japanese[29] group, initial studies on the radical reactions of this compound revealed some promise for its application as an allylating agent. However, until Keck's study,[9] the synthetic applications of compound **6** for allylation were not appreciated.

The early report by Keck[9] on the practical applications of **6** involved the now typical conditions where the radical precursor and the allylstannane are refluxed in toluene or benzene in the presence of AIBN. Sometimes the reaction can be photo-initiated at room temperature without AIBN. Since this report, many examples of the application of **6** have been described, and a few representative illustrations are given below [(a)-(c)].

(a)[30]

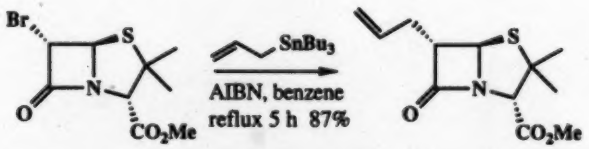


Eq.3

(b)[31]

Eq. 4

(c)[13b]



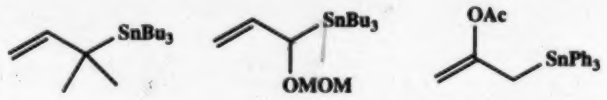
Eq. 5

As Keck's early findings revealed that the radical allylating conditions are compatible with a wide variety of functional groups, e.g., acetals, ketals, ethers, epoxides, lactones, hydroxyl groups, esters and sulfonate esters, it was not difficult for free radical allylation to find immediate acceptance.

In order to study the scope and limitations of free radical allylations, Migita and coworkers[32] have conducted a number of experiments in which various organic halides were subjected to reaction with the allylstannane **6** and the crotylstannane **7**. Their findings revealed that under similar conditions, polyhalomethanes, α-haloesters and α-halonitriles give better yields in the reaction with allyltins, compared to aryl, benzyl and alkyl halides. Generally, compound **6** gives superior results to compound **7**, and this observation was interpreted on the basis of steric crowding at the olefinic site. However, as described by Keck,[25a] compound **7** also acts as a good hydrogen donor towards carbon radicals, and this fact contributes to the poorer performance of **7** with respect to **6**.

6 **7**

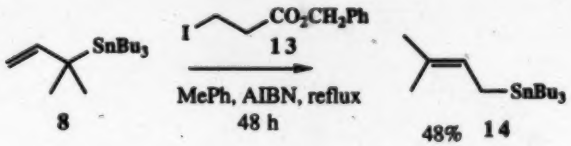
Later, Baldwin and coworkers[19] reported their findings with the allylstannanes **8** - **12**. While Migita[32] found that substitution at C(3) was



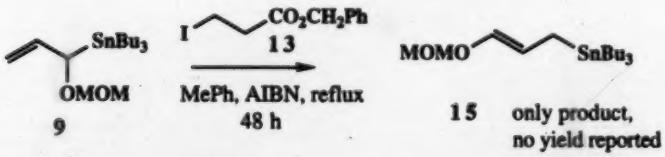
8 **9** **10**

11 **12**

detrimental to the reactivity of an allylstannane, Baldwin found the same to be true with substitution at the C(1) (i.e., the allylic carbon carrying the tin substituent). Thus, when **8** (eq. 6) or **9** (eq. 7) were treated with benzyl 3-iodopropionate (**13**)

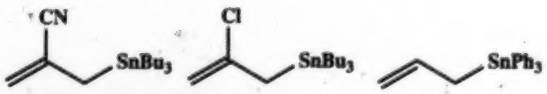


8 48% **14** Eq. 6



9 **15** only product, no yield reported Eq. 7

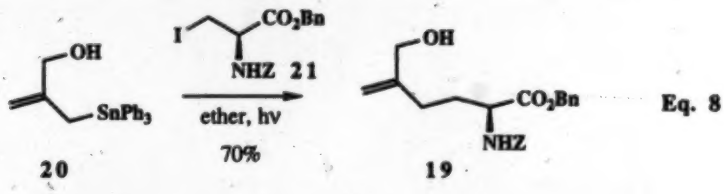
under the standard thermal conditions, the major product obtained in each case was the rearrangement product **14** or **15**, respectively, and no addition of the carbon radical to the allylic stannane was observed. While substitution at C(2), as in **10**, **11** and **12**, might be thought satisfactory due to the degeneracy of the rearrangement products, Baldwin observed that only **11** and **12**, both of which have electron-withdrawing groups at C(2), reacted with alkyl halides. Compound **10** gave no useful allyl transfer. Following these findings, a few more allylating agents, **16** and **17**, were



16 17 18

made[33] and compared with **18**. Using 2-bromo-*N*-benzoylglycine as a carbon radical source, Baldwin found that product yields were highest with **16** (74%), followed by **18** (65%) and then **17** (50%), but no explanation was provided for the observed trend.

Recently, in their preparation of tabtoxinine β-lactam, Baldwin and coworkers[34] were able to obtain a 70% yield of **19** (eq. 8) by irradiation of a 3:1 mixture of **20** and **21** in ether with a medium pressure mercury lamp.

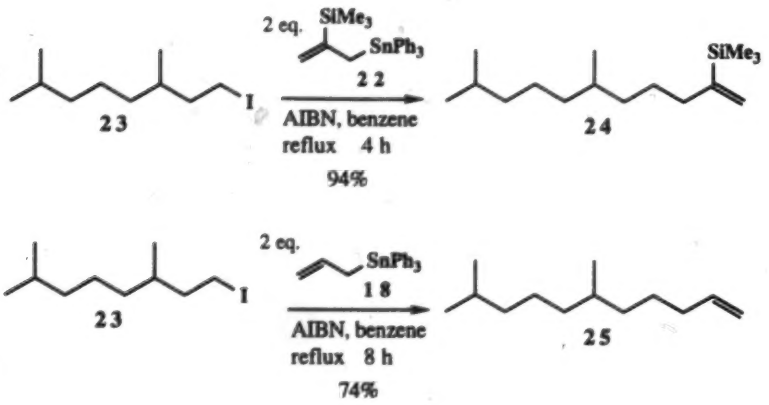


20 19 Eq. 8

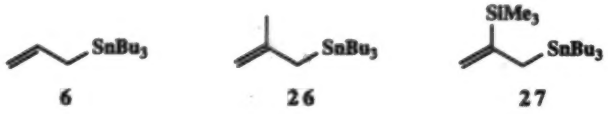
In their search to find other useful allylating agents, Lee and coworkers[35] compared the synthetic applications of **22** and **18** in radical allylations. They found

22 18

that substitution of the allylstannane at C(2) with a trimethylsilyl group significantly enhances the reactivity towards carbon radicals, and a better yield was obtained after only half of the usual reaction time. Thus, reaction of 3,7-dimethyl-1-iodooctane **23**



with **22** (eq. 9) for 4 hours in refluxing benzene gave the vinylsilane **24** in 94% yield, while with **18**, an 8 hour reaction time provided **25** in only 74% yield (eq. 10). A more detailed comparison was conducted by Renaud and coworkers.[36] In their study, they compared the allylation rates of **6**, **26**, and **27** in reactions with nucleophilic, electrophilic and neutral radicals. The results of their measurements can be summarized as follows:



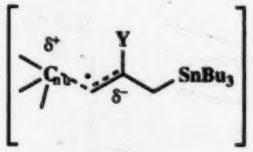
(a) Regardless of the nature of the attacking radical, the presence of the trimethylsilyl group at C(2), as in **27**, enhances the reactivity relative to the allylstannane **6**. The degree of enhancement is greater with nucleophilic and electrophilic radicals and less when the radical is neutral in these respects.

(b) With a methyl group at the C(2), a rate enhancement relative to **6** was observed only when the attacking radical is electrophilic.

Unfortunately, no direct study comparing **6** with **26** was conducted. However, based on the above results, we can deduce that with an electrophilic radical, **26** would react faster than **6**.

A partially polarized transition state was suggested to explain the above findings.

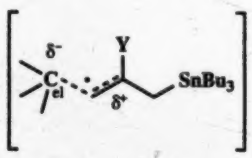
Fig. I-1



nucleophilic radicals

28 Y = $SiMe_3$
29 Y = H
30 Y = Me

Fig. I-2

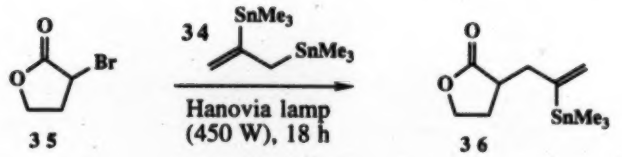


electrophilic radicals

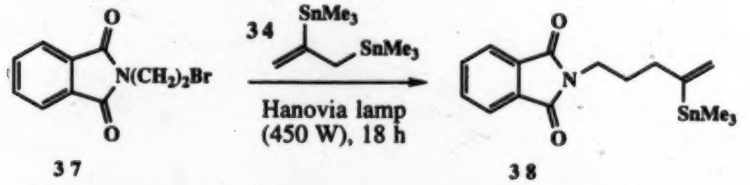
31 Y = $SiMe_3$
32 Y = H
33 Y = Me

With a nucleophilic radical, the transition state in Figure I-1 would be stabilized by a trimethylsilyl group at C(2) (**28**).[37] Such stabilization would not be present with a hydrogen at C(2) (see **29**) and, with a methyl group (see **30**), we would expect some destabilization. On the other hand, with an electrophilic radical, the polarized transition state in Figure I-2 would be more stable with a methyl group (see **33**) at C(2) than with a trimethylsilyl group (see **31**) or a hydrogen (see **32**). Indeed, it has been shown that in such a situation, a methyl group is more stabilizing than a trimethylsilyl group, followed by a hydrogen, whose effect was set at the baseline.[38] This study by Renaud and coworkers provides a theoretical basis for radical allylations.

Prior to Renaud's report, Curran had investigated reagent **34**.[20] Allylation of **35** with **34** gave **36** in 72% yield (eq. 11), while **38** was formed in 41% yield (eq. 12). Electrophilic radicals generally perform better than nucleophilic radicals.

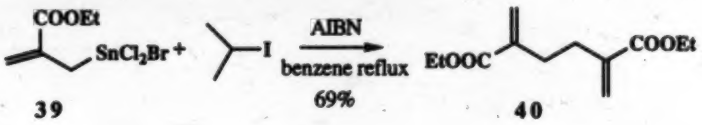


Eq. 11

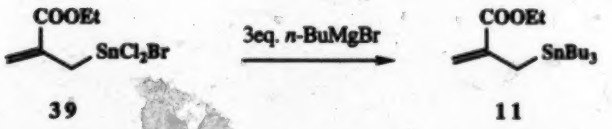


Eq. 12

Against the background of Baldwin's report on the favorable effect of having an electron-withdrawing group at C(2) of an allylating agent,[19] Fouquet and coworkers explored the possibility of applying the easily prepared **39** in radical allylations. Unfortunately, reaction with isopropyl iodide (eq. 13) under Keck's conditions, afforded nothing but the dimer **40** in 69% yield. However, **39** can easily be converted into the synthetically useful **11**[39] by treatment with 3 equivalents of *n*-BuMgBr (eq. 14). This technique constitutes a novel and convenient preparation of allylating agents similar to **11** via allyltin trihalides.[21]



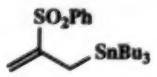
Eq. 13



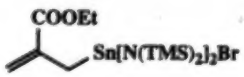
Eq. 14

Finally, other interesting C(2) substituted allylstannanes are the phenylsulfonylated propene **41**, reported by Padwa,[40] and **42**, reported by Fouquet.[22] With **41**, under the usual allylating conditions (AIBN/benzene, reflux or

hn), allylated products were formed in satisfactory yields. With **42**, several bromoalkanes were allylated, and products were also obtained in satisfactory yields.



41



42

II. RESULTS AND DISCUSSION

In the light of the above survey, Paul[41] had explored the synthetic utility of the allyl-silane stannane reagent **1** in radical allylations. Table I-4 lists all her allylation results.

Table I-4 Allylation results with reagent 1

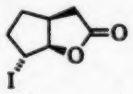
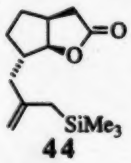
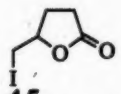
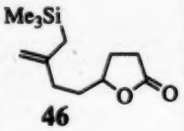
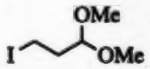
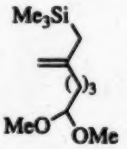
Substrate	Conditions	Product	Yield
 **43**	2.3 eq. **1**, benzene, 5-10 °C sunlamp 15 h	 **44**	68%
 **45**	2 eq. **1**, benzene, 5-10 °C Hanovia 17 h	 **46**	75%
 **47**	3 eq. **1**, benzene, r.t. Hanovia 20 h --- 2 eq. **1** AIBN, benzene, 5-10 °C Hanovia 12 h	 **48**	50% --- 72%

Table I-4 (Continued)

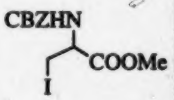
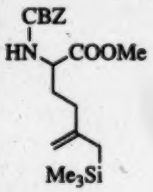
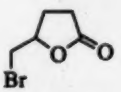
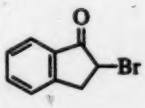
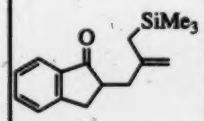
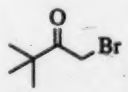
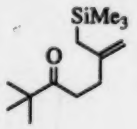
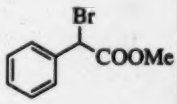
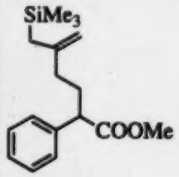
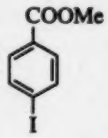
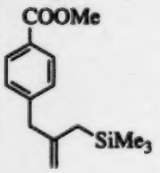
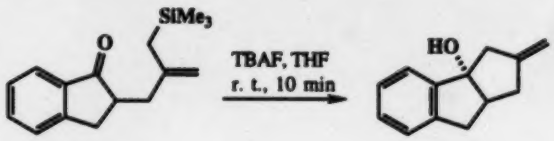
Substrate	Conditions	Product	Yield
 **49**	2.5 eq. **1**, benzene, r. t. Hanovia 16 h ---------- 3 eq. **1**, AIBN, benzene, 5-10 °C Hanovia 20 h	 **50**	7% ----- 74%
 **51**	2.5 eq. **1**, benzene, 5-10 °C Hanovia 21 h ---------- 2 eq. **1**, AIBN, benzene, 5-10 °C Hanovia 8 h	**46**	6% ----- 55%
 **52**	2.0 eq. **1**, benzene, 5-10 °C sunlamp 3 h ---------- 2.0 eq. **1**, AIBN benzene, reflux 2 h	 **53**	86% ----- 68%

Table I-4 (Continued)

Substrate	Conditions	Product	Yield
 **54**	2.5 eq. **1**, benzene, r. t. Hanovia 15 h	 **55**	59%
 **56**	2.5 eq. **1**, benzene r. t. Hanovia 23 h	 **57**	26%
 **58**	2 eq. **1**, benzene, 5-10 °C sunlamp 24 h --- 4 eq. **1**, benzene, 5-10 °C, Hanovia 24 h	 **59**	19% --- 20%

She also found that **53** can be transformed into tricyclic alcohol **60** in 74% yield by treatment with TBAF (Scheme I-2). This reaction illustrates that allylylsilane



53 **60**

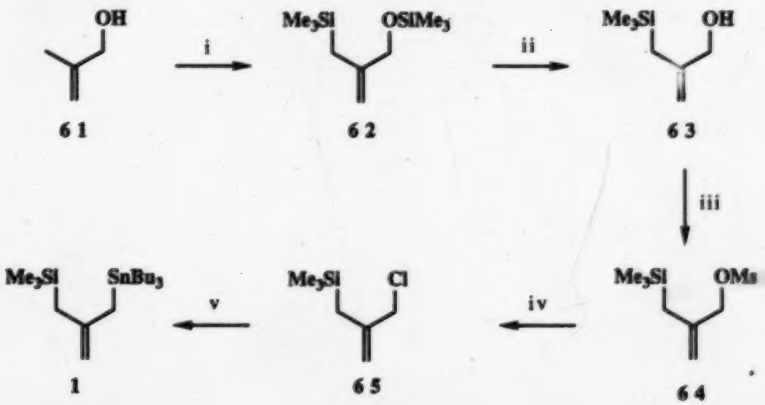
Scheme I-2

53, made by radical allylation with reagent **1**, can be functionalized further. Compound **60** is clearly synthetically equivalent to an α,β-unsaturated ketone, that would be available by ozonolysis and dehydration.

It seems that the best conditions of allylation with reagent **1** (2 eq.) are: AIBN (0.2 eq.), 5-10 °C , system degassed, and irradiation with a Hanovia UV quartz lamp[42] (140 W), as shown by the behavior of **47**, **49**, and **51**. Our main objectives were: (a) to find which reagent, **1** or **2**, is better for radical allylations, and (b) to explore the type of substrates that will react nicely with the better reagent under the established allylation conditions.

Preparation of trimethyl[2-[(tributylstannyl)methyl]-2-propenyl]silane (1)

The preparation of reagent **1**, following Paul's procedure,[41] is summarized in Scheme I-3.



Scheme I-3 *Reagents and conditions*: i, BuLi, TMEDA; TMSCl, 48%; ii, H_2SO_4, THF, 83%; iii, MsCl, Et_3N, CH_2Cl_2, 90%; iv, LiCl, THF, 70%; v, Bu_3SnLi, THF, 71%.

Compound **61** was treated with BuLi, followed by chlorotrimethylsilane in the presence of TMEDA, to give **62** in 48% yield. The trimethylsilyl group on oxygen of compound **62** was taken off by stirring for 1.5 h in THF in the presence of H_2SO_4. Alcohol **63** was then converted into mesylate **64** in 90% yield, by treatment with distilled mesyl chloride in CH_2Cl_2 in the presence of triethylamine. Mesylate **64** was then stirred overnight with lithium chloride in THF to afford **65** in 70% yield. Further conversion of chloride **65** was done by treatment with lithium tributylstannylide, itself prepared from LDA and tributyltin hydride in THF, to afford **1** in 71% yield, but with slight impurities.

Preparation of trimethyl[2-[(triphenylstannyl)methyl]-2-propenyl]silane (2)

Reagent **2** was prepared by the same route as reagent **1** (Scheme I-3), except for the last step. Hence, reagent **2** was formed by treatment of chloride **65** with sodium triphenylstannylide in THF (Scheme I-4) in 79% yield, but also with slight impurities.

65 2

Scheme I-4 *Reagents and conditions*: Ph_3SnH, NaH, THF, 79%.

Compounds **1** and **2** should be purified by distillation, since they decompose during flash chromatography over silica gel, but they may be stored in a freezer for up to 8 weeks without appreciable decomposition. Older material should be redistilled before use. We observed that compounds **1** and **2** still contained slight impurities

even after two Kugelrohr distillations under vacuum. Fortunately, however, these do not seem to affect subsequent reactions.

Radical allylations with reagents 1 and 2

The first substrate we tried was methyl 2,3,4-tri-*O*-acetyl-6-deoxyl-6-iodo-α-D-glucopyranoside (**66**). All our radical allylation results with reagents **1** and **2** are listed in Table I-5.

Table I-5 Allylation results of compound 66 with reagents 1 and 2

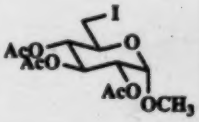
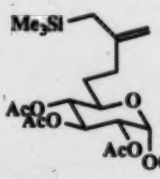
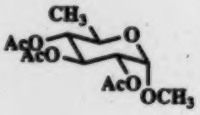
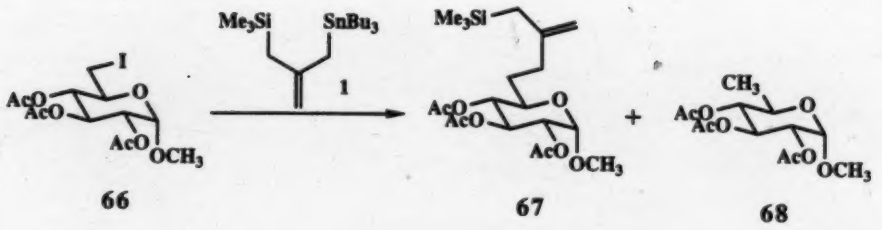
Entry	Substrate	Conditions	Product	Yield
1	 **66**	2 eq. **1**, AIBN, CH_3CN-PhH, 15-20 °C, Hanovia 21 h	 **67** ----------  **68**	27% ----- 47%
2	**66**	2 eq. **1**, $Bu_3SnSnBu_3$, DME, r. t., Rayonet 23 h	**67** ---------- **68**	25% ------ 67%

Table I-5 (Continued)

Entry	Substrate	Conditions	Product	Yield
3	**66**	2 eq. **1**, ABCC, DME, 15-20 °C, Hanovia, 7 h	**67** ---------- **68**	28% ------ 69%
4	**66**	4 eq. **1**, AIBN, DME, 15-20 °C, Hanovia, 9 h	**67** ---------- **68**	45% ------ 51%
5	**66**	6 eq. **1**, AIBN, DME, 15-20 °C, Hanovia, 30 h	**67** ---------- **68**	46% ------ 50%
6	**66**	4 eq. **2**, AIBN, DME, 15-20 °C, Hanovia, 20 h	**67** ---------- **68**	52% ------ 42%

At first, we used Paul's radical allylation conditions: AIBN (0.2 eq) in CH_3CN-PhH,[43] system degassed, irradiation with Hanovia Lamp at 15-20 °C[44] for 21 h, the ratio of **1** to substrate **66** being 2:1. Surprisingly, we obtained allylation product **67** in only 27% yield, along with a reduced compound **68** in 47% yield (Scheme I-5).



Scheme I-5

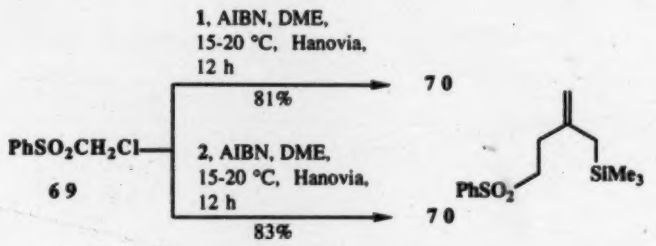
We wondered if this result was specific to the substrate or was due to a poor choice of radical initiator. Therefore, we modified Paul's radical allylation conditions by using hexabutylditin in DME, and a Rayonet reactor (3000 Å)[45] for irradiation for 23 h. The desired allylation product was obtained in only 25% yield, and along with the reduced compound **68** in 67% yield (Table I-5, entry 2).

The next conditions we used were: ABCC in DME instead of AIBN in CH_3CN-PhH, and irradiation with a Hanovia lamp at 15-20 °C for 7 h. The yield (Table I-5, entry 3) was not improved.

We realized that allylation of **66** with reagent **1** competed with reduction, so we decided to use more than 2 equivalents of allylating agent **1**. We decided to use Paul's allylation conditions but with DME as solvent and a 4:1 ratio of **1** to substrate **66**. After irradiation with a Hanovia Lamp at 15-20 °C for 9 h, we obtained the desired product in 45% yield, along with the reduced compound in 51% yield (Table I-5, entry 4). These conditions were the best so far, and there was no further improvement even we used a 6:1 ratio of **1** to substrate **66** (Table I-5, entry 5).

In order to compare the reactivity of allylating agents **1** and **2**, we did allylation experiments with substrate **66** and reagent **2**, using the best conditions we had established, and obtained compound **67** and **68** in 52% and 42% yield, respectively (Table I-5, entry 6). Further comparison was done by radical allylations

of substrate **69** with reagents **1** and **2**, respectively (Scheme I-6). Compound **70** was obtained in 81% yield by reaction with reagent **1**, and in 85% yield by reaction with reagent **2**.



Scheme I-6

From the above studies, our impression is that the performance of compound **2** in radical allylations may be slightly better than the performance of compound **1**. We then decided to examine the reactivity of compound **2** with a few other substrates under the established conditions.

By considering the partially polarized allylation transition state proposed by Renaud (page 11, Fig.I-1 and Fig.I-2), in terms of electrophilic radical substrates, the substituent at C(2) of compound **2** would be expected to stabilize a partial positive charge that develops at C(2) in the transition state. We would anticipate, therefore, that electrophilic radicals should be more favored for our type of radical allylations with compound **2**. At this point, we turned to several readily available compounds, **71 - 76**, so that we could quickly screen the reactivity of reagent **2**. The allylation results are listed in Table I-6.

Table I-6 Allylation results of different substrates with reagent 2

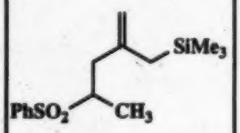
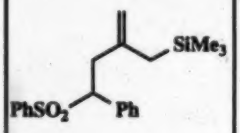
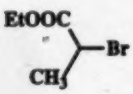
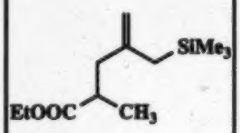
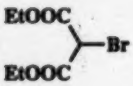
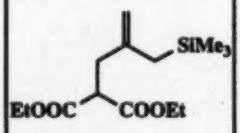
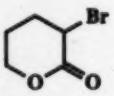
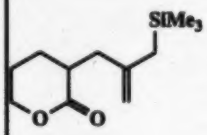
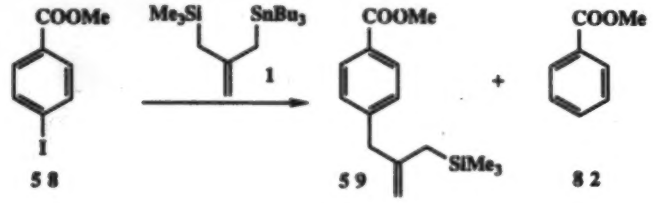
Entry	Substrate	Conditions	Product	Yield
1	$PhSO_2CH(Cl)CH_3$ **71**	4 eq. **2**, AIBN, DME, 15-20 °C, Hanovia 24 h	 **77**	70%
2	$PhSO_2CH(Cl)Ph$ **72**	4 eq. **2**, AIBN, DME, 15-20 °C, Hanovia 25 h	 **78**	43%
3	 **73**	4 eq. **2**, AIBN, DME, 15-20 °C, Hanovia, 20 h	 **79**	70%
4	 **74**	4 eq. **2**, AIBN, DME, 15-20 °C, Hanovia, 8 h	 **80**	90%
5	 **75**	4 eq. **2**, AIBN, DME, 15-20 °C, Hanovia, 12 h	 **81**	81%

Table I-6 (Continued)

Entry	Substrate	Conditions	Product	Yield
6	$CH_3OCH(Br)CN$ **76**	4 eq. **2**, AIBN, DME, 15-20 °C, Hanovia, 12 h	complex mixture	

All substrates, except compounds **72** and **76**, gave good allylation yields. The reason that compound **72** gave a poor allylation yield is not yet clear; the result is similar to the case of compound **56**, and the radical stabilities in the two cases are very close. We are surprised that 2-bromo-2-methoxyacetonitrile **76** led to a complex mixture.

We also reexamined compound **58**. The yield of the allylation product was improved by the following allylation conditions: ABCC (0.2 eq) in DME, system degassed, Rayonet reactor, irradiation at room temperature for 24 h, the ratio of **1** to substrate **58** being 4:1. A mixture of 51% allylation product **59** and 47% methyl benzoate **82** was obtained (^{1}H NMR analysis) (Scheme I-7).



Scheme I-7

As we realized that compound **58** was not an ideal substrate in this case, no further work was done with **58**.

III. CONCLUSION

The examples of photo-initiated allylation that we have surveyed indicate that the best conditions for allylation involve photochemical initiation at a temperature below 20 °C, using a medium pressure mercury lamp with Pyrex filtration and in the presence of AIBN, the ratio of **2** to substrate being 4:1. The reactions may be run in PhH or DME. Electrophilic radicals generally behave well (Table I-6, entries 1-5 and compound **69**), and the reaction is reliable in such cases. Compound **58** gave a poor yield, and compound **76** led to a complex mixture, the reasons for these two observations are not yet clear.

IV. EXPERIMENTAL

General procedures. Unless stated to the contrary, the following conditions apply: Reactions were carried out under a slight static pressure of Ar that had been purified by passage through a column (3.5 x 42 cm) of R-311 catalyst[46] and then through a similar column of Drierite. Glassware was dried in an oven for at least 3 h before use (120 °C) and either cooled in a desiccator over Drierite, or assembled quickly, sealed with rubber septa, and allowed to cool under a slight static pressure of Ar. Reaction mixtures were stirred by Teflon-coated magnetic stirring bars.

Hexane used for chromatography was distilled before use.

Products were isolated from solution by evaporation under water-aspirator vacuum at, or below, room temperature, using a rotary evaporator.

Cannula transfers were done under slight pressure (Ar), not by suction.

The following photochemical equipment was used: (a) Rayonet reactor, 3000 Å, four 21-W lamps used), (b) Hanovia, medium pressure Hg lamp, type SH (140 W), and (c) General Electric sunlamp (275 W).

Commercial thin layer chromatography (TLC) plates (silica gel, Merck 60F–254) were used. Spots were detected by spraying the plate with a solution of phosphomolybdic acid[47] or *p*-anisaldehyde,[48] followed by charring with a heat gun, or by examination under UV light. Silica gel for flash chromatography was Merck type 60 (230-400 mesh).

Dry solvents were prepared under an inert atmosphere and transferred by syringe or cannula. Dry THF and PhH were distilled from sodium and benzophenone ketyl. MeCN was distilled from CaH_2.

FTIR measurements were made as casts from the specified solvent using potassium bromide plates.

The symbols s', d', t', and q' used for ^{13}C NMR signals indicate zero, one, two, or three attached hydrogens, respectively.

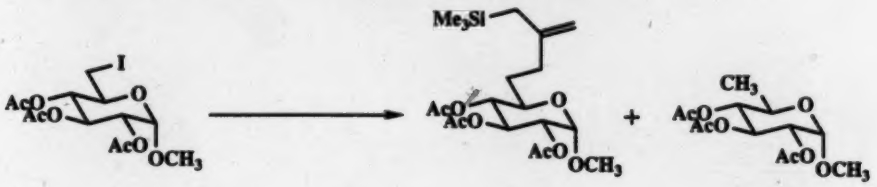
Trimethyl[2-[(triphenylstannyl)methyl]-2-propenylsilane (2).

65 **2**

NaH (60%w/w dispersion in oil) (192 mg, 4.8 mmol), in a dry round-bottomed flask (50 mL), was washed with dry THF (3 x 5 mL) under Ar, and then suspended (magnetic stirring) in THF (10 mL). A solution of Ph_3SnH (1.40 g, 4.0 mmol) in THF (2 mL) was added by cannula at 0 °C over 1 min. The cold bath was removed, and stirring was continued for 30 min. A solution of **65**[41] (845.2 mg, 5.2 mmol) in THF (2 mL) was added by cannula at 0 °C over ca. 2 min, the cold bath was removed, and stirring was continued for 6 h. The mixture was diluted with water (1 mL), and extracted with Et_2O (2 x 5 mL). The organic extract was dried (Na_2SO_4) and evaporated. The residue was diluted with acetone, and the insoluble material was filtered off and washed by acetone. Evaporation of the combined filtrates, and Kugelrohr distillation of the residue (oil-pump) gave **2** (1.5070 g, 79%) as a colorless oil containing slight impurities (^1H NMR, 360 MHz): bp 145-152 °C (0.3 mmHg); FTIR (CH_2Cl_2 cast) 1612 cm^{-1}; ^1H NMR (C_6D_6, 360 MHz) δ -0.02 (s, 9 H), 1.55 (s, 2 H), 2.49 (s, $^2J_{SnCH}$ = 36 Hz, 2 H), 4.51-4.57 (m, $^4J_{SnCCCH}$ = 10.2 Hz, 1 H), 4.78-4.85 (m, $^4J_{SnCCCH}$ = 11.3 Hz, 1 H), 7.13-7.23 (m, 9 H), 7.55-7.71 (m, 6 H); ^{13}C NMR (C_6D_6, 75.5 MHz) δ -1.27 (q'), 24.09 (t'), 29.37 (t'), 106.40 (t'), 128.85 (d'), 129.25 (d', $^3J_{SnCCC}$ = 5 Hz), 137.43 (d', $^2J_{SnCC}$ =

17 Hz), 139.26 (s', $^1J_{SnC}$ = 1460.7 Hz), 145.55 (s'); exact mass *m/z* calcd for $C_{25}H_{30}Si^{120}Sn$ 478.11389, found 478.11394.

Methyl 2,3,4-Tri-*O*-acetyl-6,7,8,9-tetradeoxy-8-(trimethylsilylmethyl)-α-D-gluco-non-8-enepyranoside (67).



66 67 68

(a) Use of 1. Methyl 2,3,4-tri-*O*-acetyl-6-deoxy-6-iodo-α-D-glucopyranoside[49] (**66**) (100 mg, 0.23 mmol), AIBN (3.8 mg, 0.023 mmol), and **1** (384.8 mg, 0.92 mmol) in dry DME (1 mL), contained in a Pyrex test tube (1 x 10 cm) closed by a septum, was degassed with a vigorous stream of Ar, which was passed through the solution for 6 min. The mixture was then irradiated (Hanovia, 140 W) for 9 h at 15-20 °C (cold water bath). The resulting cloudy solution, containing some white precipitate, was diluted with Et_2O (2 mL), and DBU (3 drops) was added with shaking. The solid was filtered off and washed with Et_2O. Evaporation of the filtrate and flash chromatography of the residue over silica gel (1.5 x 23 cm), using 1:4 EtOAc-hexane, gave methyl 2,3,4-tri-*O*-acetyl-6-deoxy-α-D-glucopyranoside[50] (**68**) (36 mg, 51%) as a pure (^{1}H NMR, 300 MHz), colorless oil. The fraction containing **67** was rechromatographed over silica gel (0.5 x 14 cm), using 2:98 Et_2O-CH_2Cl_2, to give **67** (45.4 mg, 45%) as a pure (^{1}H NMR, 300 MHz), colorless oil.

Compound **67** had: FTIR (CH_2Cl_2 cast) 1754, 1633, 1225 cm^{-1}; ^1H NMR (C_6D_6, 360 MHz) δ 0.03 (s, 9 H), 1.51 (s, 2 H), 1.61-1.85 (m, 11 H), 1.98-2.08 (m, 1 H), 2.27-2.34 (m, 1 H), 2.99 (s, 3 H), 3.75-3.81 (m, 1 H), 4.65 (s, 1 H), 4.75 (dd, *J* = 2.8, 1.3 Hz, 1 H), 4.88 (d, *J* = 3.7 Hz, 1 H), 5.07 (dd, *J* = 10.3, 3.7 Hz, 1 H), 5.14 (dd, *J* = 9.9, 9.4 Hz, 1 H), 5.88 (dd, *J* = 10.3, 9.4 Hz, 1 H); ^{13}C NMR (C_6D_6, 75.5 MHz) δ -1.32 (q'), 20.21 (q'), 20.37 (q'), 26.94 (t'), 29.87 (t'), 33.86 (t'), 54.86 (q'), 68.35 (d'), 70.84 (d'), 71.69 (d'), 72.77 (d'), 96.99 (d'), 107.88 (t'), 146.94 (s'), 169.35 (s'), 169.68 (s'), 169.75 (s'); exact mass *m/z* calcd for $C_{20}H_{34}O_8Si$ 430.20230, found 430.20232.

Compound **68**[50] had: FTIR (CH_2Cl_2 cast) 1751, 1248, 1225 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.19 (d, *J* = 6.3 Hz, 3 H), 2.00 (s, 3 H), 2.03 (s, 3 H), 2.06 (s, 3 H), 3.38 (s, 3 H), 3.82-3.95 (m, 1 H), 4.79 (dd, *J* = 9.6, 9.6 Hz, 1 H), 4.83-4.89 (m, 2 H), 5.39-5.46 (m, 1 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 17.19 (q'), 20.69 (q'), 55.24 (q'), 64.90 (d'), 70.07 (d'), 71.23 (d'), 73.80 (d'), 96.59 (d'), 169.84 (s'), 170.09 (s'), 170.19 (s'); exact mass *m/z* calcd for $C_{12}H_{17}O_7$ 273.09744 (M - OCH_3), found 273.09718.

(b) Use of 2. The above procedure was followed, using **66**[49] (60 mg, 0.14 mmol), AIBN (4.6 mg, 0.028 mmol), **2** (267 mg, 0.56 mmol), and DME (0.8 mL), with an irradiation time of 20 h. The resulting cloudy solution, containing some white precipitate, was diluted with Et_2O (2 mL), and DBU (3 drops) was added with shaking. The solid was filtered off and washed with Et_2O. Evaporation of the solvent and flash chromatography of the residue over silica gel (1 x 23 cm), using 3:7 EtOAc-hexane, gave **68** (31 mg, 52%) as a pure (^1H NMR, 300 MHz), colorless oil. The fraction containing **67** was rechromatographed over silica gel (0.5 x 14 cm), using 2:98 Et_2O-CH_2Cl_2, to give **67** (18 mg, 42%) as a pure (^1H NMR, 300 MHz), colorless oil.

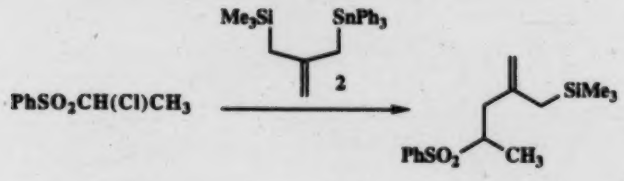
Phenyl 3-(trimethylsilylmethyl)-3-butenyl sulfone (70).

69 70

(a) Use of 1. The procedure for **67** was followed, using **69**[51] (60 mg, 0.31 mmol), AIBN (10 mg, 0.062 mmol), **1** (518.6 mg, 1.24 mmol), dry DME (2 mL), and an irradiation period (Hanovia, 140 W) of 12 h. The resulting cloudy solution, containing some white precipitate, was diluted with Et_2O (2 mL), and DBU (3 drops) was added with shaking. The solid was filtered off and washed with Et_2O. Evaporation of the filtrate and flash chromatography of the residue over silica gel (1.0 x 23 cm), using 1:9 EtOAc-hexane, gave **70** (71 mg, 81%) as a pure (^1H NMR, 300 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 1635, 1151, 1308 cm^{-1}; ^1H NMR (C_6D_6, 300 MHz) δ -0.15 (s, 9 H), 1.21 (s, 2 H), 2.31-2.38 (m, 2 H), 2.90-3.00 (m, 2 H), 4.33-4.35 (m, 1 H), 4.43-4.44 (m, 1 H), 6.85-6.95 (m, 3 H), 7.74-7.80 (m, 2 H); ^{13}C NMR (C_6D_6, 50.3 MHz) δ -1.62 (q'), 26.74 (t'), 31.13 (t'), 54.99 (t'), 108.69 (t'), 128.29 (d'), 128.48 (d'), 133.16 (d'), 140.23 (s'), 143.79 (s'); exact mass *m/z* calcd for $C_{14}H_{22}O_2SSi$ 282.11099, found 282.11109.

(b) Use of 2. The above procedure was followed, using **69**[51] (60 mg, 0.31 mmol), AIBN (10 mg, 0.062 mmol), **2** (591.5 mg, 1.24 mmol), and dry DME (2 mL), with an irradiation period (Hanovia, 140 W) of 12 h. The resulting cloudy solution, containing some white precipitate, was diluted with Et_2O (2 mL), and DBU (3 drops) was added with shaking. The solid was filtered off and washed with Et_2O. Evaporation of the filtrate and flash chromatography of the residue over silica gel (1.0 x 23 cm), using 1:9 EtOAc-hexane, gave **70** (74.5 mg, 85%) as a pure (^1H NMR, 300 MHz), colorless oil.

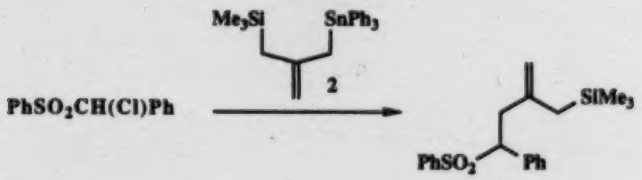
Phenyl 4-(trimethylsilylmethyl)-4-penten-2-yl sulfone (77).



71 77

The procedure for **67** was followed, using **71**[52] (35 mg, 0.17 mmol), AIBN (6 mg, 0.034 mmol), **2** (326 mg, 0.68 mmol), dry DME (0.5 mL), and an irradiation period (Hanovia, 140 W) of 24 h. The resulting cloudy solution, containing some white precipitate, was diluted with Et_2O (2 mL), and DBU (3 drops) was added with shaking. The solid was filtered off and washed with Et_2O. Evaporation of the filtrate and flash chromatography of the residue over silica gel (1.0 x 23 cm), using 1:9 EtOAc-hexane, gave **77** (35 mg, 70%) as a pure (^1H NMR, 360 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 1633, 1305, 1148 cm^{-1}; ^1H NMR (C_6D_6, 360 MHz) δ -0.13 (s, 9 H), 1.12-1.34 (m, 5 H), 2.10 (dd, J = 13.6, 11.5 Hz, 1 H), 2.79 (d, J = 13.6 Hz, 1 H), 3.07-3.16 (m, 1 H), 4.50-4.58 (m, 2 H), 6.82-6.98 (m, 3 H), 7.75-7.80(m, 2 H); ^{13}C NMR (C_6D_6, 50.3 MHz) δ -1.58 (q'), 12.73 (q'), 25.76 (t'), 38.37 (t'), 58.35 (d'), 111.11 (t'), 128.94 (d'), 129.29 (d'), 133.07 (d'), 138.49 (s'), 142.68 (s'); exact mass *m/z* calcd for $C_{15}H_{24}O_2SSi$ 296.12662, found 296.12674.

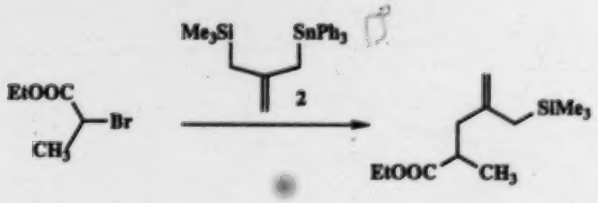
Phenyl 1-phenyl-3-(trimethylsilylmethyl)-3-butenyl sulfone (78).



72 78

The procedure for **67** was followed, using **72**[53] (51 mg, 0.19 mmol), AIBN (6 mg, 0.038 mmol), **2** (362.5 mg, 0.76 mmol), and dry DME (4 mL), with an irradiation period (Hanovia, 140 W) of 25 h. The resulting cloudy solution, containing some white precipitate, was diluted with Et_2O (2 mL), and DBU (3 drops) was added with shaking. The solid was filtered off and washed with Et_2O. Evaporation of the filtrate and flash chromatography of the residue over silica gel (1.0 x 23 cm), using 5:95 EtOAc-hexane, followed by recrystallization from hexane, gave **78** (29 mg, 43%) as a pure (^1H NMR, 300 MHz), white solid: mp 109-110 °C; FTIR (CH_2Cl_2 cast) 1634, 1146 cm^{-1}; ^1H NMR (CD_2Cl_2, 300 MHz) δ -0.05 (s, 9 H), 1.37 (d, J = 0.6 Hz, 2 H), 2.82 (ddd, J = 14.7, 11.8, 0.8 Hz, 1 H), 2.92-3.00 (m, 1 H), 4.25 (dd, J = 11.8, 3.3 Hz, 1 H), 4.42-4.46 (m, 2 H), 7.10-7.63 (m, 10 H); ^{13}C NMR (CD_2Cl_2, 100.6 MHz) δ -1.46 (q'), 26.56 (t'), 36.14 (t'), 70.28 (d'), 111.16 (t'), 128.59 (d'), 129.05 (d'), 129.20 (d'), 129.45 (d'), 130.52 (d'), 132.43 (s'), 133.81 (d'), 137.89 (s'), 142.58 (s'); exact mass *m/z* calcd for $C_{20}H_{26}O_2SSi$ 358.14227, found 358.14335.

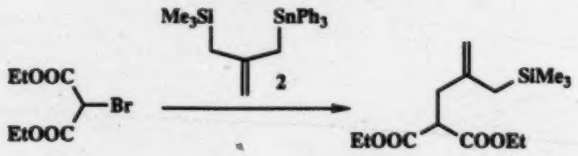
Ethyl 2-Methyl-4-(trimethylsilylmethyl)-4-pentenoate (79).



73 79

The procedure for **67** was followed, using **73** (50 mg, 0.28 mmol), AIBN (9 mg, 0.056 mmol), **2** (527 mg, 1.10 mmol), and dry DME (1.5 mL), with an irradiation period (Hanovia, 140 W) of 20 h. The resulting cloudy solution, containing some white precipitate, was diluted with Et_2O (2 mL), and DBU (3 drops) was added with shaking. The solid was filtered off and washed with Et_2O. Evaporation of the solvent and flash chromatography of the residue over silica gel (1.0 x 23 cm), using 1:99 EtOAc-hexane, and again over silica gel (0.5 x 14 cm), using 1:300 Et_2O-hexane, gave **79** (45 mg, 70%) as a pure (^{1}H NMR, 300 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 1736, 1633 cm^{-1}; ^{1}H NMR (CD_2Cl_2, 300 MHz) δ 0.02 (s, 9 H), 1.11 (d, *J* = 7.0 Hz, 3 H), 1.22 (t, *J* = 7.0 Hz, 3 H), 1.52 (dd, *J* = 1.0, 1.0 Hz, 2 H), 1.99 (ddd, *J* = 14.5, 7.4, 1.0 Hz, 1 H), 2.37 (dddd, *J* = 14.5, 7.4, 1.3, 0.6 Hz, 1 H), 2.56-2.68 (m, 1 H), 4.02-4.15 (m, 2 H), 4.56-4.60 (m, 2 H); ^{13}C NMR (CD_2Cl_2, 75.5 MHz) δ -1.33 (q'), 14.43(q'), 17.18 (q'), 26.77 (t'), 38.33 (d'), 42.57 (t'),60.46 (t') 109.01 (t'), 145.44 (s'), 176.60 (s'); exact mass *m/z* calcd for $C_{12}H_{24}O_2Si$ 228.15456, found 228.15462.

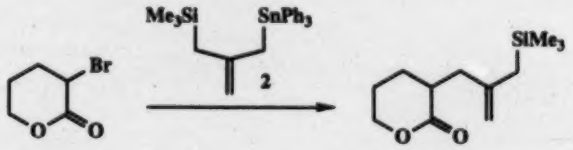
Dimethyl 2-[2-(Trimethylsilylmethyl)-2-propenyl)]-malonate (80).



74 80

The procedure for **67** was followed, using **74**[54] (72 mg, 0.34 mmol), AIBN (11 mg, 0.068 mmol), **2** (648.7 mg, 1.36 mmol), and dry PhH (1.5 mL), with an irradiation period (Hanovia, 140 W) of 8 h. The resulting cloudy solution, containing some white precipitate, was diluted with Et_2O (2 mL), and DBU (3 drops) was added with shaking. The solid was filtered off and washed with Et_2O. Evaporation of the solvent and flash chromatography of the residue over silica gel (1.0 x 23 cm), using 5:95 EtOAc-hexane, gave **80** (78.8 mg, 90%) as a pure (^{1}H NMR, 200 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 1756, 1740, 1636 cm^{-1}; ^{1}H NMR (C_6D_6, 200 MHz) δ -0.02 (s, 9 H), 1.44 (d, J = 0.6 Hz, 2 H), 2.75(d, J = 7.7 Hz, 2 H), 3.29 (s, 3 H), 3.72 (t, J = 7.7 Hz, 1 H), 4.62-4.76 (m, 2 H); ^{13}C NMR (C_6D_6, 75.5 MHz) δ -1.48 (q'), 27.08 (t'), 37.25 (t'), 50.78 (d'), 51.94 (q'), 108.81 (t'), 144.21 (s'), 169.36 (s'); exact mass *m/z* calcd for $C_{12}H_{22}O_4Si$ 258.12872, found 258.12876.

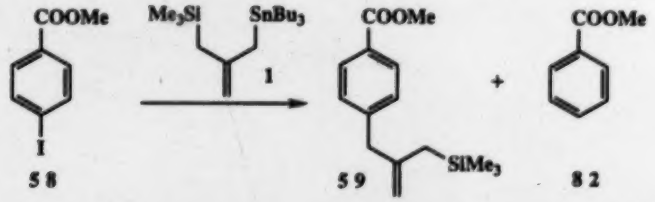
2-[2-(Trimethylsilylmethyl)-2-propenyl]-d-valerolactone (81).



75 81

The procedure for **67** was followed, using **81**[55] (43 mg, 0.24 mmol), AIBN (7.9 mg, 0.048 mmol), **2** (343.7 mg, 0.72 mmol), and dry DME (0.5 mL), with an irradiation period (Hanovia, 140 W) of 12 h. The resulting cloudy solution, containing some white precipitate, was diluted with Et_2O (2 mL), and DBU (3 drops) was added with shaking. The solid was filtered off and washed with Et_2O. Evaporation of the solvent and flash chromatography of the residue over silica gel (1.0 x 23 cm), using 1:9 EtOAc-hexane, gave **81** (44.2 mg, 81%) as a pure (^1H NMR, 300 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 1736, 1633 cm^{-1}; ^1H NMR (C_6D_6, 300 MHz) δ 0.05 (s, 9 H), 0.93-1.22 (m, 3 H), 1.33-1.45 (m, 2 H), 1.49-1.58 (m, 1 H), 2.00 (dd, J = 14.5, 9.9 Hz, 1 H), 2.22-2.33 (m, 1 H), 2.81 (dd, J = 14.5, 3.6 Hz, 1 H), 3.65 (t, J = 6.0, 2 H), 4.56-4.63 (m, 2 H); ^{13}C NMR (C_6D_6, 75.5 MHz) δ -1.36 (q'), 21.88 (t'), 24.38 (t'), 26.18 (t'), 37.92 (d'), 40.22 (t'), 67.66 (t'), 109.62 (t'), 144.69 (s'), 172.85 (s'); exact mass *m/z* calcd for $C_{12}H_{22}O_2Si$ 226.13892, found 226.13877.

Methyl 4-[2-(Trimethylsilylmethyl)-2-propenyl]benzoate (59).



A solution of **58** (100 mg, 0.38 mmol), **1** (638.5 mg, 1.53 mmol), and 1,1'-azobis(cyclohexanecarbonitrile) (19 mg, 0.076 mmol) in dry DME (0.8 mL), contained in a Pyrex test tube (1 x 10 cm) closed by a septum, was degassed with a vigorous stream of Ar, which was passed through the solution for 6 min. The mixture was then irradiated for 24 h at room temperature (Rayonet, 3000 Å). The resulting cloudy mixture was diluted with Et_2O (2 mL), and DBU (3 drops) was added with shaking. The resulting solid was filtered off, and washed with Et_2O. Evaporation of the filtrate and flash chromatography of the residue over silica gel (1.5 x 23 cm), using 1:4:200 Et_3N-EtOAc-hexane, gave a mixture of **59** and **82** (75 mg). The material contained 51 mol% **59** and 47 mol% **82** as judged by its ^1H NMR (360 MHz) spectrum.

In another experiment, a pure (^1H NMR, 400 MHz) sample of **59** was obtained as a colorless oil by flash chromatography over silica gel, using 1.5:98.5 EtOAc-hexane: FTIR (hexane cast) 1725 cm^{-1}; ^1H NMR (acetone-d_6, 400 MHz) δ 0.05 (s, 9 H), 1.52 (s, 2 H), 3.38 (s, 2 H), 3.86 (s, 3 H), 4.60 (br s, 1 H), 4.66 (br s, 1 H), 7.34 (br d, J = 8.34 Hz, 2 H), 7.94 (br d, J = 8.34 Hz, 2 H); ^{13}C NMR (acetone-d_6, 75.5 MHz) δ -1.21 (q'), 26.66 (t'), 45.44 (t'), 52.17 (q'), 110.33 (t'), 129.16 (s'), 130.13 (d'), 130.21 (d'), 146.39 (s'), 147.22 (s'), 167.18 (s'); exact mass, *m/z* calcd for $C_{15}H_{22}O_2Si$ 262.13892, found 262.13842.

V. REFERENCES AND FOOTNOTES

1. Sommer, L. H.; Tyler, L. J.; Whitmore, F. C. *J. Am. Chem. Soc.* **1948**, *70*, 2872.
2. Deleris, G.; Dunogues, J.; Calas, R. *J. Organomet. Chem.* **1975**, *93*, 43.
3. Corriu, R. J. P.; Masse, J.; Samate, D. *J. Organomet. Chem.* **1975**, *93*, 71.
4. Hosomi, A.; Sakurai, H. *Tetrahedron Lett.* **1976**, 1295.
5. (a) Fleming, I.; Pearce, A.; Snowden, R. L. *J. Chem. Soc., Chem. Commun.* **1976**, 182; (b) Fleming, I; Paterson, I. *Synthesis* **1979**, 446.
6. Langkopf, E.; Schinzer, D. *Chem. Rev.* **1995**, *95*, 1375.
7. Sarkar, T. K. *Synthesis*, **1990**, 969 (Part 1); 1101 (Part 2).
8. Kang, K.-T.; U, J. S.; Park, D. K.; Kim, J. G.; Kim, W. J. *Bull. Korean Chem. Soc.* **1995**, *16*, 464.
9. (a) Keck, G. E.; Yates, J. B. *J. Am. Chem. Soc.* **1982**, *104*, 5829.
10. (a) Chu, C. K.; Doboszewski, B.; Schmidt, W.; Ullas, G.V. *J. Org. Chem.* **1989**, *54*, 2767. (b) Fiandor, J.; Tam, S. Y. *Tetrahedron Lett.* **1990**, *31*, 597. (c) Butterfield, K.; Thomas, E. J. *Synlett* **1993**, 411. (d) De Masmaeker, A.; Lebreton, J.; Hoffman, P.; Freier, S. M. *Synlett* **1993**, 677. (e) De Masmaeker, A.; Lebreton, J.; Waldner, A.; Fritsch, V.; Wolf, R. M.; Freier, S. M. *Synlett* **1993**, 733. (f) Lebreton, J.; Waldner, A.; Lesueur, C.; De Masmaeker, A.; *Synlett* **1994**, 137. (g) Grøtli, M; Undheim, K. *Acta Chem. Scand.* **1995**, *49*, 217.
11. (a) Baldwin, J. E.; Adlington, R. M.; Lowe, C.; O'Neil, I. A.; Sanders, G. L.; Schofield, J.; Sweeney, J. B. *J. Chem. Soc., Chem. Commun.* **1988**, 1030. (b) Kano, S.; Yokomatsu, T.; Shibuya, S. *J. Org. Chem.* **1989**, *54*, 513. (c) Easton, C.J.; Scharfbillig, T.M. *J. Org. Chem.* **1990**, *55*, 384. (d)

Hamon, D.P.G.; Massy-Westropp, R.A.; Razzino, P. *Tetrahedron* **1995**, *51*, 4183.

12. Toru, T.; Yamada, Y.; Ueno, T.; Maekawa, E.; Ueno, Y, *J. Am. Chem. Soc.* **1988**, *110*, 4815.

13. (a) Hanessian, S.; Alpegiani, M. *Tetrahedron* **1986**, *27*, 4857. (b) Hanessian, S.; Alpegiani, M. *Tetrahedron Lett.* **1989**, *45*, 941.

14. Keck, G.E.; Kachensky, D.F.; Enholm, E.J. *J. Org. Chem.* **1984**, *49*, 1462.

15. Keck, G.E.; Kachensky, D.F. *J. Org. Chem.* **1986**, *51*, 2487.

16. Keck, G.E.; Enholm, E.J.; Yates, J.B.; Wiley, M.R. *Tetrahedron* **1985**, *41*, 4079.

17. Blaszczak, L.C.; Armour, H.K.; Halligan, N.G. *Tetrahedron Lett.* **1990**, *31*, 5693.

18. Landais, Y.; Planchenault, D. *Tetrahedron* **1995**, *51*, 12097.

19. Baldwin, J. E.; Adlington, R. M.; Birch, D. J.; Crawford, J. A.; Sweeney, J. B. *J. Chem. Soc., Chem. Commun.* **1986**, 1339.

20. Curran, D. P.; Yoo, B. *Tetrahedron Lett.* **1992**, *33*, 6931.

21. Fouquet, E.; Gabriel, A.; Maillard, B.; Pereyre, M. *Bull. Soc. Chim. Fr.* **1995**, *132*, 590.

22. Fouquet, E.; Pereyre, M.; Roulet, T. *J. Chem. Soc., Chem. Commun.* **1995**, 2387.

23. But compare references: (a) Fliri, H.; Mak, C.-P. *J. Org. Chem.* **1985**, *50*, 3438; (b) Yoshida, Y.; Ono, N.; Sato, F. *J. Org. Chem.* **1994**, *59*, 6153.

24. (a) see reference 19; (b) Takuwa, A.; Kanaue, T.; Nishigaichi, Y.; Iwamoto, H. *Tetrahedron Lett.* **1995**, *36*, 575.

25. (a) Keck, G.E.; Yates, J.B. *J. Organomet. Chem.* **1983**, *248*, C21. (b) see reference 11c. (c) see reference 11d.

26. Danishefsky, S.J.; Panek, J.S. *J. Am. Chem. Soc.* **1987**, *109*, 917.

27. For an exception, see reference 19.

28. Grignon, J.; Servens, C.; Pereyre, M. *J. Organomet. Chem.* **1975**, *96*, 225.

29. Kosugi, M.; Kurino, K.; Takayama, K.; Migita, T.; *J. Organomet. Chem.* **1973**, *56*, C11.

30. Moriya, O.; Kakihana, M.; Urata, Y.; Sugizaki, T.; Kageyama, T.; Ueno, Y.; Endo, T. *J. Chem. Soc., Chem. Commun.* **1985**, 1401.

31. Chai, C. L. L.; Page, D. M.; *Tetrahedron Lett.* **1993**, *34*, 4373.

32. Migita, T.; Nagai, K.; Kosugi, M. *Bull. Chem. Soc. Jpn.* **1983**, *56*, 2480.

33. Baldwin, J. E.; Adlington, R. M.; Lowe, C.; O'Neil, I. A.; Sanders, G. L.; Schofield, C. J.; Sweeney, J. B. *J. Chem. Soc., Chem. Commun.* **1988**, 1030.

34. Baldwin, J. E.; Fieldhouse, R.; Russell, A. T. *Tetrahedron Lett.* **1993**, *34*, 5491.

35. Lee, E.; Yu, S.-G.; Hur, C.-U.; Yang, S.-M. *Tetrahedron Lett.* **1988**, *29*, 6969.

36. Renaud, P.; Gerster, M.; Ribezzo, M. *Chimia* **1994**, *48*, 366.

37. White, J. M. *Aust. J. Chem.* **1995**, *48*, 1227.

38. Apeloig, Y.; Stanger, A. *J. Am. Chem. Soc.* **1985**, *107*, 2806.

39. Giese, B.; Linker, T.; Muhn, R. *Tetrahedron*, **1989**, *45*, 935.

40. Padwa, A.; Murphree, S. S.; Yeske, P. E. *Tetrahedron Lett.* **1990**, *31*, 2983.

41. Paul, C. C. Ph.D. Thesis, University of Alberta, 1996.

42. Hanovia medium pressure Hg lamp (140 W, type SH).

43. Substrate **75** was not soluble in PhH.

44. Paul's bath temperature was 5-10 °C, ours was 15-20 °C (checked by thermometer).

45. Four 21 Watt 3000 Å lamps used inside the reactor barrel.

46. Supplied by Chemical Dynamics Corporation, South Plainfield, N. J.

47. Phosphomolybdic acid (15 g) and ceric ammonium sulfate (2.5 g) dissolved in a mixture of water (985 mL) and concentrated sulfuric acid (15 mL).

48. *p*-Anisaldehyde (15 drops) were added to concentrated sulfuric acid (6 mL) and ethanol (94 mL).

49. Garegg, P.J.; Samuelsson, B. *J. Chem. Soc., Perkin Trans 1* **1980**, 2866.

50. Roberts, E.V.E.; Schwarz, J.C.P. McNab, C.A. *Carbohydr. Res.* **1968**, *7*, 311.

51. Hauske, J.R.; Rapoport, H. *J. Org. Chem.* **1979**, *44*, 2472.

52. Makosza, M.; Glinka, T.; Kinowski, A. *Tetrahedron* **1984**, *40*, 1863.

53. Tuleen, D.L.; Marcum, V.C. *J. Org. Chem.* **1967**, *32*, 204.

54. Gallus, H.P.; Macbeth, A.K. *J. Chem. Soc.* **1937**, 1810.

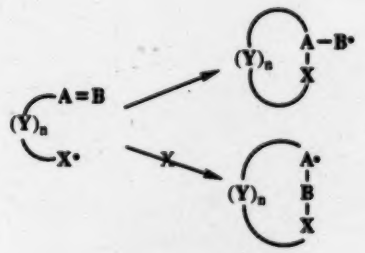
55. Wolff, J.J.; Frenking, G.; Harms, K. *Chem. Ber.* **1991**, *124*, 551.

CHAPTER 2

The Application of 5-*endo*-trigonal Radical Cyclization in Organic Synthesis

I. INTRODUCTION

In 1977, Baldwin[1] provided a concise set of rules for ring closure reactions. The rules are based on the concept that precise stereoelectronic factors determine whether a cyclization will occur easily. Baldwin's rules apply not only to heterolytic reactions but also to homolytic cyclizations. In a later work, Beckwith et al.[2] have presented some specific guidelines for radical cyclizations onto an unsaturated carbon atom, i.e., onto sp^2 or sp hybridized carbon. The disfavored nature of *endo*-trig ring closure for radical cyclizations onto carbon is a matter of general agreement,[1,2] as shown in Scheme II-1, where **Y** represents a chain of atoms ($n \leq 5$), **X** could be carbon or heteroatoms.

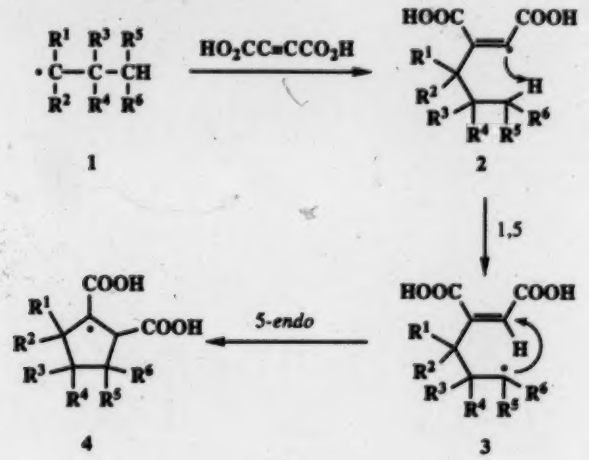


Scheme II-1

Beckwith's first guideline states:[2] "intramolecular addition under kinetic control in lower alkenyl and alkynyl radicals and related species occurs preferentially in the *exo*-mode". A few examples of the disfavoured 5-*endo*-trig radical cyclization have been reported since 1984,[3-16] and these will be discussed in the following review.

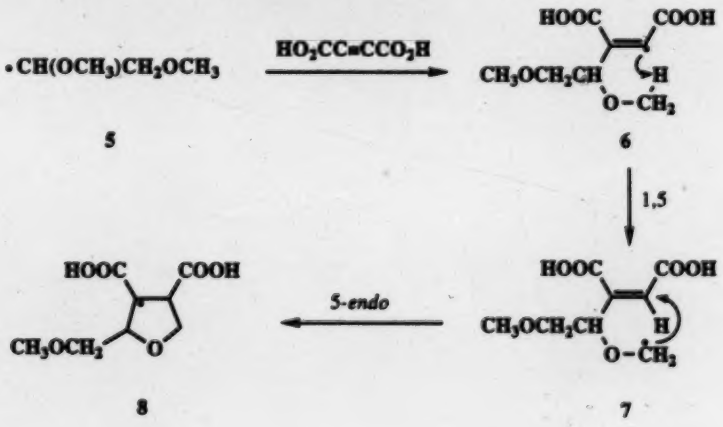
I-a. 5-*Endo*-trig cyclizations by carbon-centered radicals

Gilbert and Parry[3] studied the evidence for *endo* closure of the pent-4-enyl radicals by e.s.r. spectroscopy (Scheme II-2).



Scheme II-2

Vinyl radical **2**, generated by addition of the first-formed alkyl radical to the triple bond in butynedioic acid (**1**→**2**), underwent rapid 1,5-hydrogen shifts (**2**→**3**) and subsequent 5-*endo*-trig cyclization (**3**→**4**), to give radical **4**. 5-*Endo*-trig closure of an alkoxy radical has also been detected[4] (Scheme II-3).



Scheme II-3

The ring closure of pent-4-enyl type radicals is remarkable both for its rapidity and its *endo*-regio selectivity.

The first application of 5-*endo*-trig cyclization in natural product synthesis was an efficient synthesis of pterocarpans by Gopalsamy and Balawubramanian.[5]

9 **10**

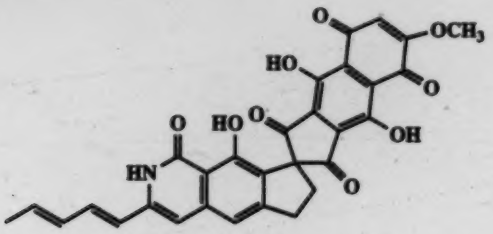
Scheme II-4

Table II-1 Synthesis of **10** via radical cyclization

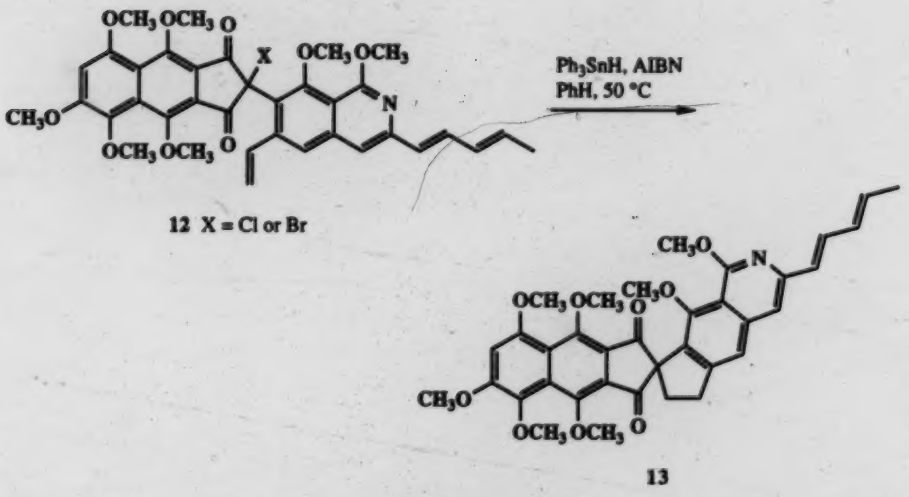
Compound **9**			**10**
R	R^1	R^2	Yield (%)
H	H	H	82
OCH_3	-CH=CH-CH=CH-		90
Cl	-CH=CH-CH=CH-		88

The 6a,11a-dihydro-6*H*-bezofuro[3,2-*c*]benzopyran (**10**) was made from precursor **9** (Scheme II-4) by a 5-*endo*-trig radical cyclization process, which was carried out by refluxing a 0.02 M solution of **9** in PhH with 1.1 equivalents of Bu_3SnH in the presence of a catalytic amount of AIBN. The cyclization proceeded smoothly in all cases (Table II-1) and no reduction product was detected.

Another example of 5-*endo*-trig radical cyclization in natural product synthesis was the synthesis of (±)-fredericamycin A (**11**) by Rao and coworkers.[6] The key step of their synthesis involved building the spiro system by an unusual 5-*endo*-trig radical cyclization (Scheme II-5).



11

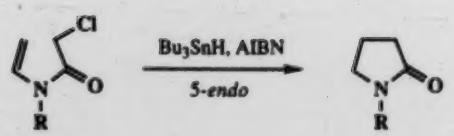


12 X = Cl or Br

13

Scheme II-5

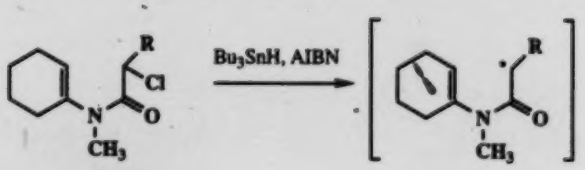
Ikeda and coworkers[7,8] investigated radical cyclizations of *N*-vinylic α-chloroacetamides, and found that compound **14** cyclized in a normally disfavored 5-*endo*-trig manner with high efficiency to give five-membered lactams **15** (Scheme II-6).



14 15

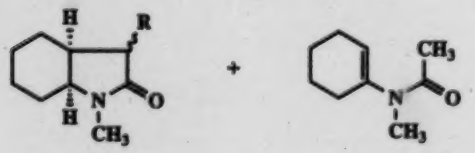
Scheme II-6

Thus, when a boiling solution of **16a** in toluene was treated with 1.1 equivalents of Bu_3SnH in the presence of a catalytic amount of AIBN, the octahydroindol-3-one **18a** was obtained in 63% yield along with the reduction product **19** (8%) (Scheme II-7).



16a, R = H
16b, R = CH_3
16c, R = Ph

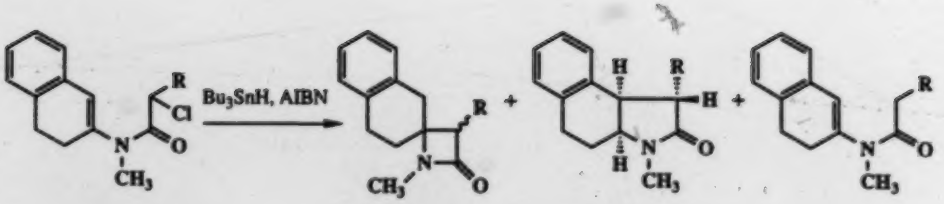
17



18a, b, c 19

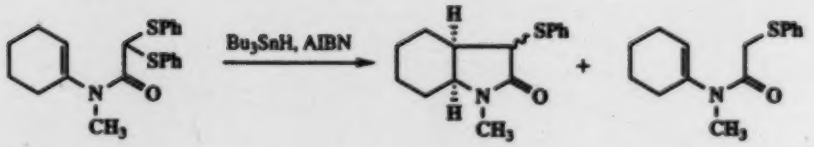
Scheme II-7

The cyclization of **16b** and **16c** occurred more cleanly to give the corresponding lactams **18b** and **18c** in 73% and 75% yields, respectively. However, compound **20a** gave no 5-*endo*-trig closure product **22a**; instead, the 4-*exo*-trig cyclization product **21a** was obtained in 50% yield along with reduction product **23a** (32%) (Scheme II-8). In the case of **20c**, 5-*endo*-trig closure occurred efficiently to give **22c** in 76% yield.



20a, R = H	21a, 50%	22a, 0%	23a, 32%
20b, R = CH_3	21b, 42%	22b, 35%	23b, 19%
20c, R = Ph	21c, 0%	22c, 76%	23c, 0%

Scheme II-8



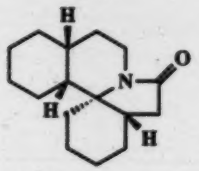
24 25 26

27 28

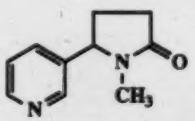
Scheme II-9

The phenylthio (PhS) group as a radical source was also examined[7] (Scheme II-9). Dithioacetal **24**, when treated with Bu_3SnH, gave the γ-lactam **25** in 59% yield, together with the reduction product **26** (6%), whereas compound **27** afforded only the reduction product **28**. It is therefore apparent that the carbonyl group incorporated into the five-membered ring plays a crucial role in effecting the 5-*endo*-trig cyclization.

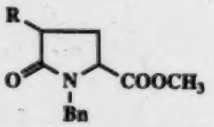
Applications of the above methodology are found in the synthesis of the erythrinane skeleton **29**,[8] (±)continine **30**,[9] and pyroglutamates **31** (R = H, Me, Ph, or Cl)[10] (Scheme II-10).



29



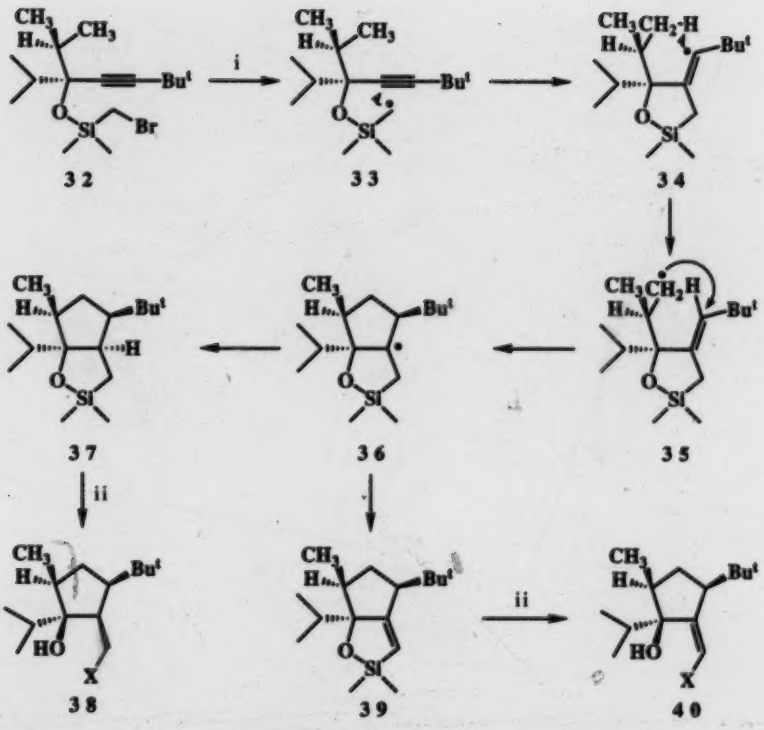
30



31

Scheme II-10

More recently, Bogen and Malacria reported[11] a 5-*endo*-trig radical cyclization pathway for the stereoselective synthesis of cyclopentanes (Scheme II-11). Radical **33**, formed from **32**, underwent 5-*exo*-dig closure (**33**→**34**); subsequent 1,5-intramolecular hydrogen migration (**34**→**35**), followed by 5-*endo*-trig cyclization (**35**→**36**) to give radical **36**. Radical **36** can either abstract hydrogen from Bu_3SnH to give compound **37**, or form a double bond adjacent to silicon to give compound **39**. Treatment of **37** and **39** with CH_3Li and H_2O_2 gave **38** in 88% yield and **40** (no yield was reported), respectively.

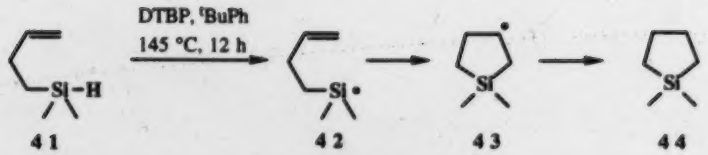


Scheme II-11 *reagents and conditions*: i, Bu_3SnH/TMS_3SiH, AIBN; ii, CH_3Li, X=$SiMe_3$; H_2O_2, X=OH.

In order to define the parameters favoring the 5-*endo*-trig radical sequence, several other substrates were also studied.

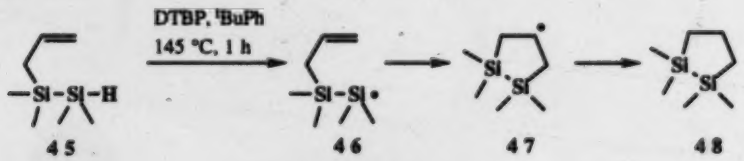
II-b. 5-*Endo*-trig cyclizations by silicon-centered radicals

Barton and Revis,[12] in determining whether the Baldwin-Beckwith rules could be extended to the cyclizations of alkenyl silicon-centered radicals, found that (3-butenyl)dimethylsilane (**41**) cyclized under thermal conditions, and gave compound **44** as a major volatile product in 18% yield (by preparative GC isolation) (Scheme II-12).



Scheme II-12

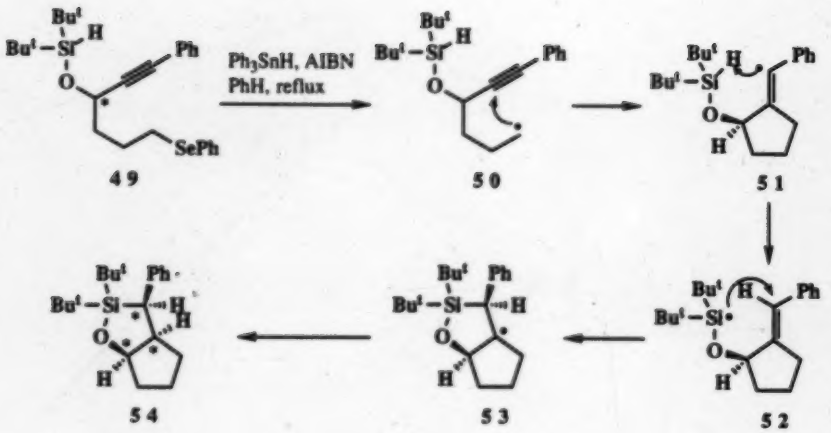
Apparently, radical **42** underwent thermodynamically controlled 5-*endo*-trig cyclization not kinetically controlled *exo* cyclization. Similarly, a solution of compound **45** in PhH (1% solution) heated at 145 °C for 1 h, in the presence of di-*tert*-butylperoxide (DTBP), afforded a mixture which contained a sole major volatile 5-*endo*-trig cyclization product **48** in 13% yield (GC) and 14% unreacted **45** (Scheme II-13).



Scheme II-13

These results coupled with those of Ingold and Davies[13] make it abundantly clear that the Baldwin-Beckwith rules for homolytic ring closure cannot be extended beneath carbon in group IV. It seems that this may be a general phenomenon for second-row elements since their radical configurations and bond lengths allow them to attain conformations which are difficult for the corresponding first-row elements.[14]

More recently, Clive and Cantin reported[15] a 5-*endo*-trig radical pathway for making substituted cyclopentanes. One representative example is illustrated in Scheme II-14.

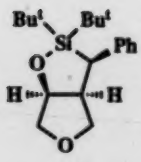


Scheme II-14

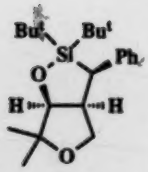
Radical **50**, generated by slow addition (2 h) of Ph_3SnH and AIBN to a refluxing solution of substrate **49** in PhH (ca. 0.01 M), underwent 5-*exo*-dig cyclization (**50→51**), intramolecular 1,5-hydrogen transfer from silicon (**51→52**), 5-*endo*-trig closure (**52→53**), and intermolecular hydrogen transfer from stannane (**53→54**), and gave product **54** in 72% yield. In this type of radical reaction, three consecutive stereogenic centers (*) of compound **54** were totally controlled by the single asymmetric center (*) of substrate **49**. This is a new means for the stereoselective synthesis of substituted cyclopentanes.

These results were reasonably attributed to a longer C-Si bond as compared with the C-C bond (1.87 Å vs 1.54 Å).

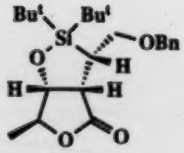
As an extension of the above methodology, Clive and Yang[16] prepared a number of five- and six-membered heterocycles containing oxygen or nitrogen (**55-59**). These results showed that substituted tetrahydrofuran, γ-lactone, pyrrolidine and chromanol systems were accessible by the method shown in Scheme II-14.


Bu^t
Bu^t
Si
O
Ph
H
H
O

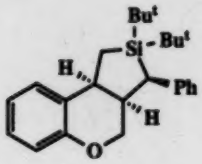
55


Bu^t
Bu^t
Si
O
Ph
H
H
O

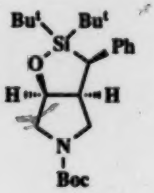
56


Bu^t
Bu^t
Si
OBn
O
H
H
H
O
O

57


Bu^t
Si
Bu^t
H
Ph
H
O

58

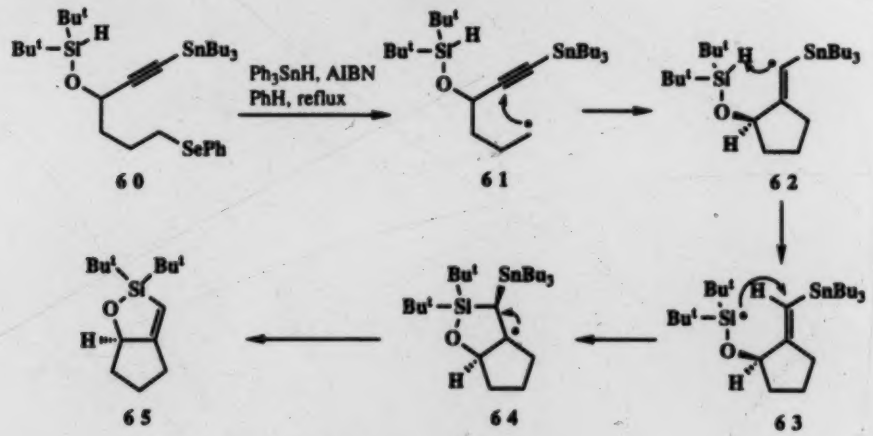

Bu^t
Bu^t
Si
O
Ph
H
H
N
Boc

59

II. RESULTS AND DISCUSSION

Clive and coworkers[15] discovered a procedure (discussed above) for making substituted cyclopentanes stereoselectively by 5-*endo*-trig cyclization with silicon centered radicals, and extended this method to make five- and six-membered heterocycles containing oxygen and nitrogen.[16] Our objective was to extend this methodology to make vinylsilanes. The chemistry of silanes has become a very extensive area, and a review has been written recently.[17] About half of this review is devoted solely to the subject of vinylsilanes; in particular, the synthetic utility of this structure unit in natural product synthesis.

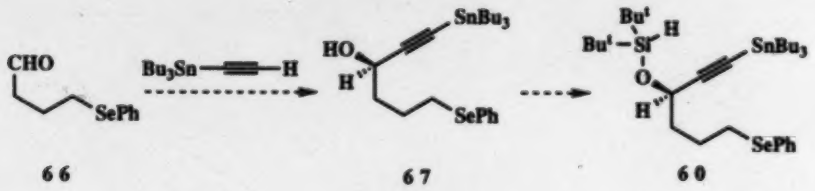
If we consider Scheme II-14, use of Bu_3Sn instead of Ph would be expected to follow the modified pathway shown in Scheme II-15. Thus, the modified sequence would lead to vinylsilanes (e.g., **65**).



Scheme II-15

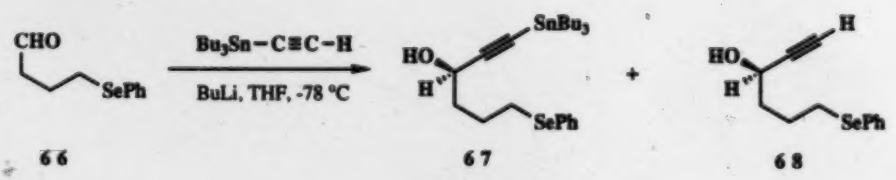
Our main task was to make compound **60** (Scheme II-16), and carry out the cyclization under the standard conditions: i.e., simultaneous slow addition (2 h) of Bu_3SnH and AIBN, both in benzene, to a solution of the substrate in refluxing benzene (0.01 M). Such an experiment should give vinylsilane **65**.

We thought of making compound **60** by the following route (Scheme II-16): Addition of lithium tributylstannylacetylide to aldehyde **66**, which was easily made from γ-butyrolactone, followed by silylation of alcohol **67**.



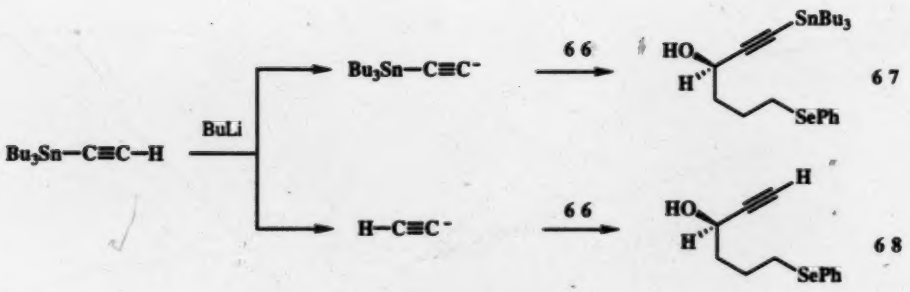
Scheme II-16

According to the above route, we made compound **66**,[18] and the addition of lithium tributylstannyl acetylide to substrate **66** in THF was conducted at -78 °C. The reaction was monitored by TLC, and it was found that a complex mixture was obtained. We assumed that compound **67** was formed but decomposed on silica gel. We then purified the crude product by flash chromatography over alumna (Al_2O_3, grade III). Product **67** was obtained in only 20% yield, together with compound **68** (54%) (Scheme II-17).



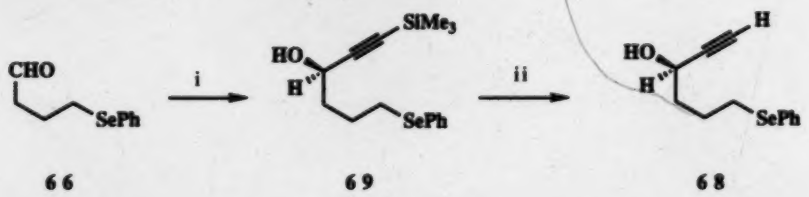
Scheme II-17

The results may indicate that two anions were generated after BuLi was added to tributylstannylacetylene (Scheme II-18), and then the addition to compound **66** occurred to give **67** and **68**, respectively. Alternatively, the tin unit of **67** may be lost during chromatography.



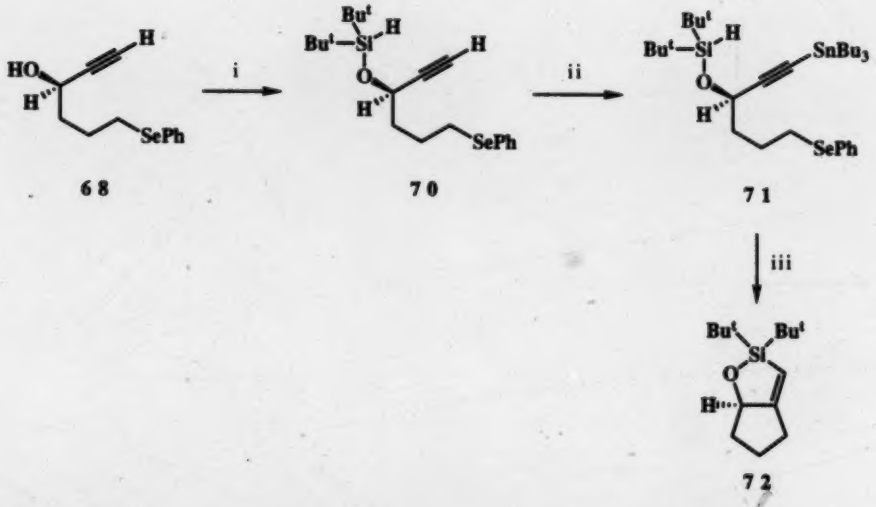
Scheme II-18

At this point, we realized that, if we could make compound **68** in good yield, we could then silylate the hydroxyl with di-*tert*-butylchlorosilane, and then attach the tin unit onto the acetylene, to give compound **60**. To this end we decided to employ trimethylsilylacetylene instead of tributylstannylacetylene. We would then proceed with desilylation by TBAF directly. Compound **68** was obtained in 83% yield (Scheme II-19) by this two-step sequence.



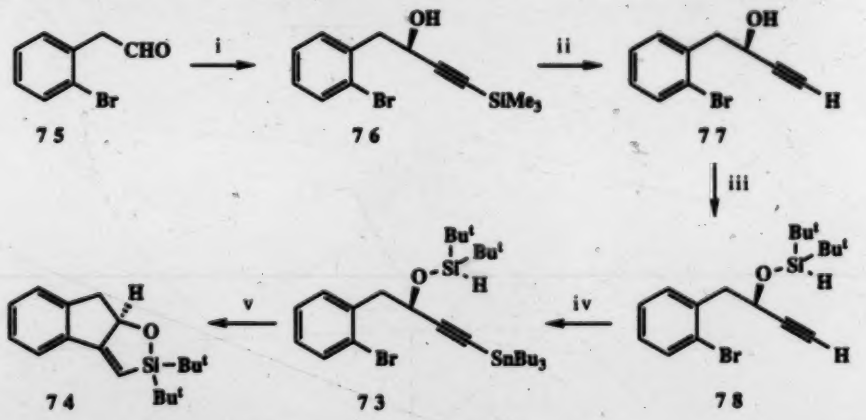
Scheme II-19 *reagents and conditions*: i, TMS-≡-H, BuLi, THF,-78 °C; ii, TBAF, THF, 0 °C.

Silylation of alcohol **68** with di-*tert*-butylchlorosilane gave compound **70** in 90% yield, and this was then treated with BuLi and Bu_3SnCl to give stannane **71**. Without further purification (compound **71** decomposed during flash chromatography over silica gel), compound **71** was cyclized under our standard conditions to give the desired vinylsilane **72** in 74% yield over two steps (Scheme II-20).



Scheme II-20 *reagents and conditions*: i, *t*-Bu_2SiHCl, imidazole, THF, reflux; ii, BuLi, Bu_3SnCl, THF, -78 °C; iii, Bu_3SnH, AIBN, PhH, reflux.

After successfully making vinylsilane **72**, we expected that compound **73** would cyclize to give vinylsilane **74**. We made aldehyde **75** by a literature procedure,[22] and then followed an analogous route to that discussed above for making **72**. In this way, vinylsilane **74** was obtained in 58% yield (Scheme II-21).

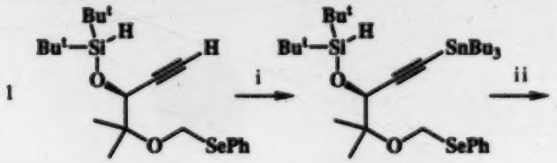
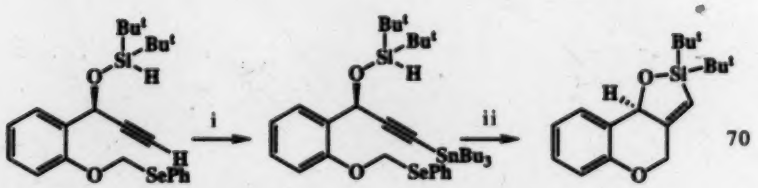
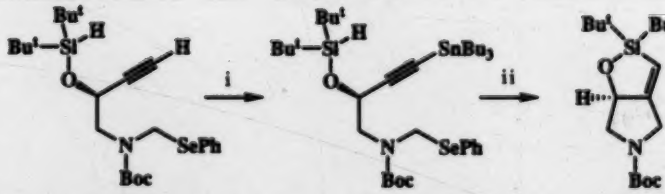


Scheme II-21 *reagents and conditions*: i, TMS-≡-H, BuLi, $CeCl_3$, THF,-78 °C; ii, TBAF, THF, 0 °C, 91%; iii, *t*-Bu_2SiHCl, imidazole, THF, reflux, 79%; iv, BuLi, Bu_3SnCl, THF, -78 °C; iii, Bu_3SnH, AIBN, PhH, reflux, 58%.

However, we had difficulties in making **76** when we used the same conditions employed for **69**, and only a 34% yield of **76** was obtained over two steps. This is probably because of enolization of aldehyde **75** when added to the base. However, when we employed cerium chloride,[19] alcohol **77** was obtained in 91% yield over two steps.

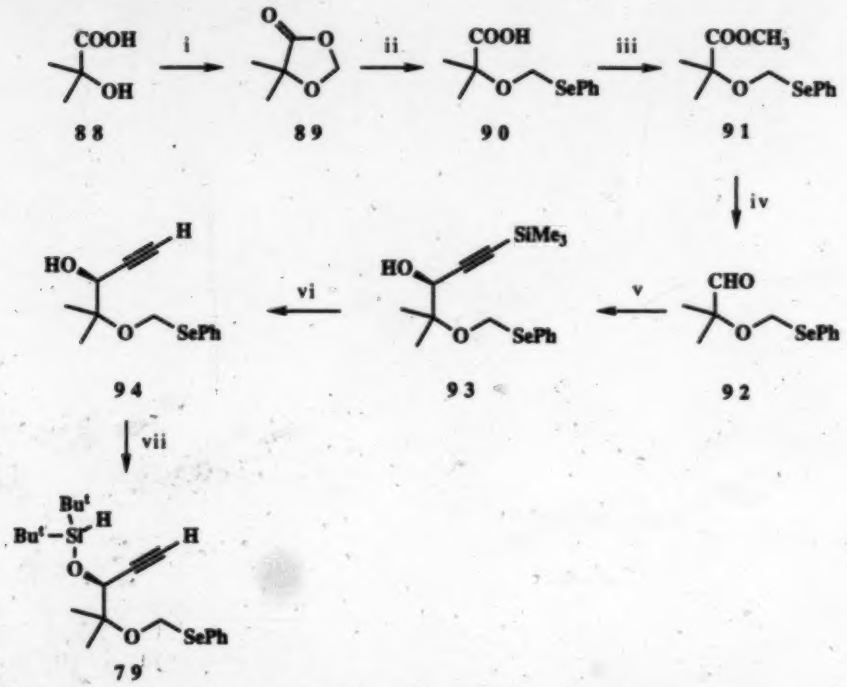
We also examined a few other substrates (**80**, **83**, **86**). They all cyclized under our standard conditions, and gave the corresponding vinylsilanes **81**, **84**, and **87**. The results are listed in Table II-2.

Table II-2 5-*endo*-trig radical cyclization

Entry	product	yield (%)
1	 **79** → **80** → **81**	82
2	 **82** → **83** → **84**	70
3	 **85** → **86** → **87**	71

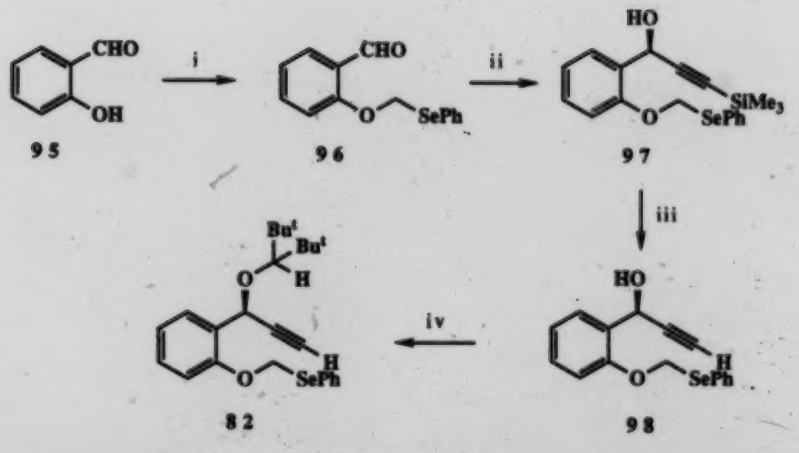
All compounds are racemic. *reagents and conditions*: i, BuLi, Bu_3SnCl, THF, -78 °C; ii, Bu_3SnH, AIBN, PhH, reflux.

All of the starting materials used in Table II-2 are readily available. In the case of entry 1 (Table II-2), the sequence of Scheme II-22 was used to prepare compound **79** via known[20] dioxolanone **89**. Ordinary lactones have often been opened[21a,b] by treatment with phenylselenide anion,[21] and it had been found in this laboratory[16] that the same reagent is very convenient for opening dioxolanones (see **89**→**90**, Scheme II-22).



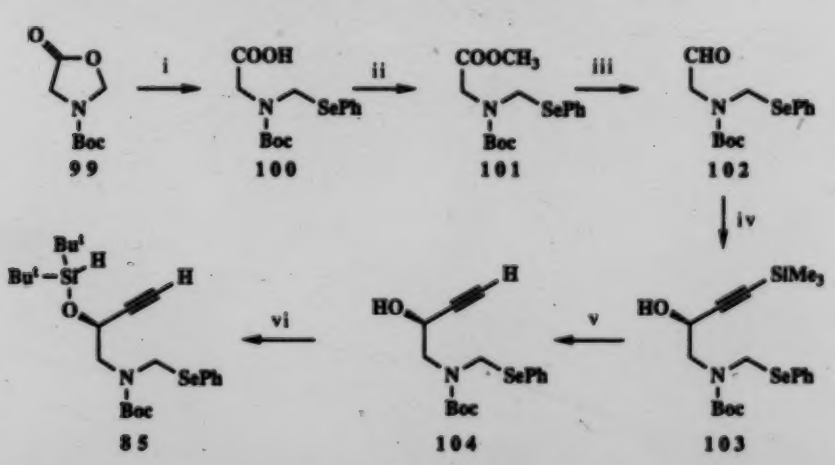
Scheme II-22 *reagents and conditions*: i, trioxane, *p*-TSA, PhH, reflux, 82%; ii, PhSeNa, HMPA, THF, reflux; iii, CH_3OH, H_2SO_4, 70% over two steps; iv, DIBAL-H, CH_2Cl_2, -78 °C, 83%; v, TMS-≡-H, BuLi, THF, -78 °C; vi, TBAF, THF, 0 °C, 90% over two steps; vii, *t*-Bu_2SiHCl, imidazole, THF, reflux, 90%.

Compound **82** was made by the route summarized in Scheme II-23.



Scheme II-23 *reagents and conditions*: i, NaH, $PhSeCH_2I$, THF, 22%; ii, TMS-≡-H, BuLi, THF, -78 °C; iii, TBAF, THF, 0 °C, 91% over two steps; iv, *t*-Bu_2SiHCl, imidazole, THF, reflux, 92%.

The nitrogen containing example **85** was available (Scheme II-24) from compound **99** by a similar route to that shown in Scheme II-22.



Scheme II-24 *reagents and conditions*: i, PhSeNa, HMPA, THF, reflux; ii, CH_3I, DBU, THF, 62% over two steps; iii, DIBAL-H, CH_2Cl_2, -78 °C, 83%; iv, TMS-≡-H, BuLi, THF, -78 °C; v, TBAF, THF, 0 °C, 90% over two steps; vi, *t*-Bu_2SiHCl, imidazole, THF, reflux, 88%.

III. CONCLUSION

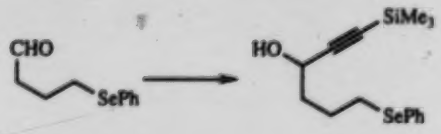
We have five examples of vinyl silanes made by 5-*endo*-trig radical cyclization, and subsequent tin extrusion. This type of reaction is a new route to vinyl silanes. Leaving groups other than Bu_3Sn need to be explored to extend this method.

Trapping vinyl silanes with electrophiles would be expected to give functionalized substituted cyclopetanes, and this process is currently being explored.

IV. EXPERIMENTAL

General procedures The same procedures as in Chapter 1 apply here.

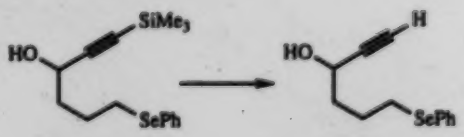
6-(Phenylseleno)-1-(trimethylsilyl)-1-hexyn-3-ol (69).



66 **69**

n-BuLi (3.13 mL, 1.6 M in hexanes, 5.0 mmol) was injected dropwise over ca. 2 min, to a stirred and cooled (-78 °C) solution of trimethylsilylacetylene (523.0 mg, 5.0 mmol) in dry THF (10 mL). After 15 min, a solution of aldehyde **66**[18] (1.14 g, 5.0 mmol) in dry THF (1.0 mL plus 1.0 mL as a rinse) was added by cannula at a rapid dropwise rate. Stirring was continued at -78 °C for 1 h. The cooling bath was removed, stirring was continued for 30 min, and then the mixture was quenched with saturated aqueous NH_4Cl (3 mL). Water (2 mL) was added, and the mixture was extracted with CH_2Cl_2 (3 x 10 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated to give crude **69**, which was used directly for the next step.

6-(Phenylseleno)-1-hexyn-3-ol (68).

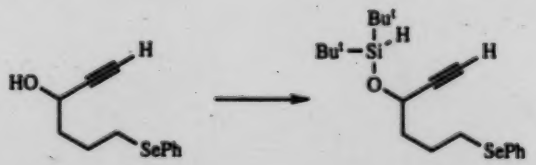


69 **68**

TBAF (7.5 mL, 1.0 M in THF, 7.5 mmol) was injected over 3 min to a stirred and cooled (0 °C) solution of all the above crude **69** in dry THF (10 mL).

Stirring was continued at 0 °C for 2 h. Water (5 mL) was added and the mixture was extracted with CH_2Cl_2 (3 x 10 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated. Flash chromatography of the residue over silica gel (4.5 x 30 cm), using 1:99 Et_2O-CH_2Cl_2, gave **68** (1.047 g, 83%) as a pure (^1H NMR, 300 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 3385, 3289, 3071, 3056, 2940, 2860, 2114, 1578, 1478, 737 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 1.78-1.95 (br, 5 H), 2.46 (d, J = 2.0 Hz, 1 H), 2.91-2.98 (m, 2 H), 4.35-4.43 (br, 1 H), 7.19-7.32 (br, 3 H), 7.45-7.55 (br, 2 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 25.59 (t'), 27.38 (t'), 37.40 (t'), 61.75 (d'), 73.27 (d'), 84.48 (s'), 126.84 (d'), 129.04 (d'), 130.14 (s'), 132.68 (d'); exact mass *m/z* cacld for $C_{12}H_{14}O^{80}Se$ 254.02089, found 254.02117.

Bis(1,1-dimethylethyl)[3-[6-(phenylseleno)-1-hexynyl]oxy]silane (70).

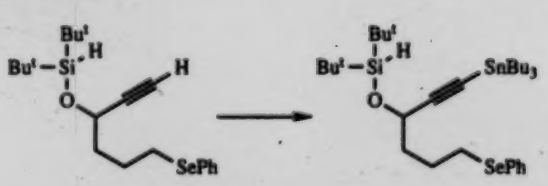


68 **70**

t-Bu_2SiHCl (1.24 mL, 6.15 mmol) was injected into a stirred solution of alcohol **68** (1.0400 g, 4.1 mmol) and imidazole (559.0 mg, 8.2 mmol) in dry THF (30 mL). A white precipitate formed after a few minutes, and ca. 5 min after the addition of the silane, the mixture was refluxed for 2 h and cooled to room temperature. Water (10 mL) was added, and the mixture was extracted with Et_2O (3 x 20 mL). The combined organic extracts were dried (Na_2SO_4) and evaporated. Flash chromatography of the residue over silica gel (4.5 x 30 cm), using 2:98 EtOAc-hexane, gave **70** (1.4516 g, 90%) as a pure (^1H NMR, 300 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 3309, 2962, 2929, 2890, 2856, 2094, 1580, 1471, 826, 735

cm^{-1}; ^1H NMR (CD_2Cl_2, 300 MHz) δ 0.98 (s, 9 H), 1.02 (s, 9 H), 1.75-1.93 (br, 4 H), 2.46 (d, *J* = 2.0 Hz, 1 H), 2.96 (t, *J* = 6.9 Hz, 2 H), 4.06 (s, 1H), 4.5 (ddd, *J* = 5.7, 5.7, 2.0, Hz, 1 H), 7.21-7.30 (br, 3 H), 7.46-7.53 (br, 2 H); ^{13}C NMR ($CDCl_3$, 50.3 MHz) δ 19.71 (s'), 20.00 (s'), 25.39 (t'), 27.22 (q'), two peaks coincide), 27.61 (t'), 38.10 (t'), 65.51 (d'), 73.00 (d'), 84.25 (s'), 126.75 (d'), 128.99 (d'), 130.27 (s'), 132.68 (d'); exact mass *m/z* cacld for $C_{20}H_{32}O^{80}SeSi$ 396.13876, found 396.13842.

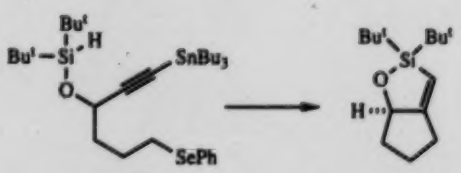
Bis(1,1-dimethylethyl)[3-[6-(phenylseleno)-1-(tributylstannyl)-1-hexynyl]oxy]silane (71).



70 **71**

n-BuLi (0.33 mL, 1.6 M in hexanes, 0.53 mmol) was injected dropwise over ca. 20 sec to a stirred and cooled (-78 °C) solution of alcohol **70** (197.8 mg, 0.50 mmol) in dry THF (1.0 mL). The mixture was stirred at -78 °C for 15 min, and a solution of Bu_3SnCl (0.15 mL, 0.53 mmol) in dry THF (0.5 mL plus 0.5 mL as a rinse) was then added by cannula at a rapid dropwise rate. Stirring was continued at -78 °C for 20 min after the addition, and the mixture was then quenched with water (1 mL). The cooling bath was removed, stirring was continued while the mixture reached room temperature (ca. 30 min), and the mixture was then extracted with Et_2O (3 x 5 mL). The combined organic extracts were dried (Na_2SO_4) and evaporated, to give **71** (350 mg) as a crude, colorless oil, which was used in the next step without further purification. The compound was not stable to silica chromatography.

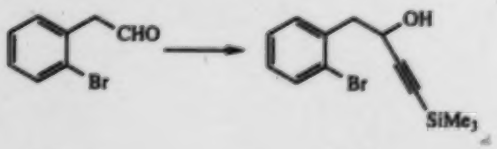
2,2-Bis(1,1-dimethylethyl)-4,5,6,6a-tetrahydro-2*H*-cyclopent[*d*]-1,2-oxasilole (72).



71 **72**

Separate solutions of Bu_3SnH (0.14 mL, 0.50 mmol) in dry PhH (7.0 mL) and AIBN (82.1 mg, 0.50 mmol) in dry PhH (7.0 mL), were injected simultaneously by double syringe pump over 2 h to a refluxing solution of the above crude acetylenic stannane **71** (350 mg) in dry PhH (50 mL). Refluxing was continued for 3 h after the addition, and the reaction mixture was cooled, and evaporated. Flash chromatography of the residue over silica gel (1.0 x 20 cm), using 30:70 CH_2Cl_2-hexane, gave **72** (92.0 mg, 77%) as a pure (^1H NMR, 300 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 2960, 2931, 2890, 2857, 1612, 1108, 1076, 824 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 0.99 (s, 9 H), 1.02 (s, 9 H), 1.19-1.35 (m, 1 H), 1.75-1.92 (br, 2 H), 2.00-2.12 (m, 1 H), 2.20-2.45 (m, 2 H), 4.72-4.82 (m, 1 H), 5.50-5.56 (m, 1 H); ^{13}C NMR ($CDCl_3$, 75.5 MHz) δ 19.90 (s'), 21.62 (s'), 21.71 (t'), 25.53 (t'), 27.33 (q'), 27.68 (q'), 31.83 (t'), 87.49 (d'), 113.77 (d'), 170.12 (s'); exact mass *m/z* cacld for $C_{14}H_{26}OSi$ 238.17529, found 238.17610. Anal. Cacld for $C_{14}H_{26}OSi$: C, 70.52; H, 10.99. Found: C, 70.72; H, 10.99.

1-(2-Bromophenyl)-4-trimethylsilyl-3-butyn-2-ol (76).

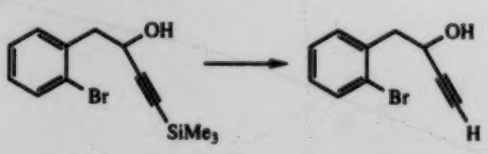


75 **76**

$CeCl_3 \cdot 7H_2O$ (0.94 g, 2.5 mmol) was placed in a 50 mL round-bottomed flask closed with a bent adaptor, and equipped with a Teflon-coated magnetic stirring bar, and the salt was dried for 5 h with gentle stirring (oil bath at 140 °C, 0.05 mmHg). The flask was cooled to room temperature under Ar, and the bent adaptor was quickly replaced by a rubber septum (Ar atmosphere). THF (5 mL) was injected, and the mixture was stirred overnight.

n-BuLi (1.13 mL, 1.6 M in hexanes, 1.8 mmol) was injected dropwise into a stirred and cooled (-78 °C) solution of trimethylsilylacetylene (229.4 mg, 2.2 mmol) in THF (2 mL). The mixture was stirred at -78 °C for 15 min, and was then added by cannula over ca. 2 min to the stirred and cooled (-78 °C) suspension of $CeCl_3$. The mixture was stirred at -78 °C for 1 h, and a solution of **75**[22] (199.0 mg, 1.0 mmol) in dry THF (1.0 mL plus 1.0 mL as a rinse) was added by cannula at a rapid dropwise rate. The mixture was stirred at -78 °C for 1 h, and quenched with water (10 mL). The mixture was extracted with CH_2Cl_2 (3 x 10 mL), and the combined organic extracts were dried ($MgSO_4$) and evaporated to give crude **76**, which was used directly for the next step.

1-(2-Bromophenyl)-3-butyn-2-ol (77).



76 **77**

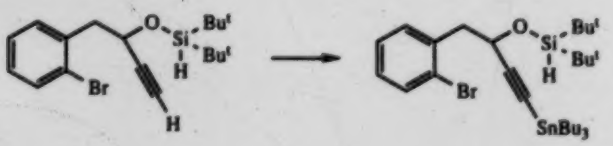
The procedure described for **68** was followed, using crude **76**, dry THF (3 mL), and TBAF (3.0 mL, 1.0 M in THF, 3.0 mmol). The mixture was stirred at 0 °C for 2 h. Water (5 mL) was added, and the mixture was extracted with CH_2Cl_2 (3 x 10 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated. Flash chromatography of the residue over silica gel (2.0 x 25 cm), using 25:75 EtOAc-hexane, gave **77** (205.0 mg, 91%) as a pure (^1H NMR, 300 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 3365, 3295, 3057, 2960, 2932, 2117, 1567, 1029 cm^{-1}; ^1H NMR (CD_2Cl_2, 300 MHz) δ 2.05 (d, J = 5.7 Hz, 1 H), 2.54 (d, J = 2.1 Hz, 1 H), 3.17 (d, J = 6.3 Hz, 2 H), 4.63-4.73 (m, 1 H), 7.15 (ddd, J = 7.9, 7.4, 1.9 Hz, 1 H), 7.29 (ddd, J = 7.5, 7.4, 1.3 Hz, 1 H), 7.36 (dd, J = 7.5, 1.9 Hz, 1 H), 7.57 (dd, J = 7.9, 1.3 Hz, 1 H); ^{13}C NMR (CD_2Cl_2, 75.5 MHz) δ 44.40 (t'), 61.89 (d'), 73.85 (d'), 84.41 (s'), 125.18 (s'), 127.75 (d'), 129.04 (d'), 132.63 (d'), 133.14 (d'), 136.60 (s'); exact mass *m/z* cacld for $C_{10}H_9O^{79}Br$ 223.98367, found 223.98371.

Bis(1,1-dimethylethyl)[2-[1-(2-bromophenyl)-3-butynyl]oxy]silane (78).

77 **78**

The procedure described for **70** was followed, using **77** (135.0 mg, 0.6 mmol), imidazole (81.7 mg, 1.20 mmol), *t*-Bu_2SiHCl (0.18 mL, 0.90 mmol), and THF (5.0 mL). The mixture was refluxed for 2.5 h and then cooled to room temperature. Water (10 mL) was added, and the mixture was extracted with Et_2O (3 x 10 mL). The combined organic extracts were dried (Na_2SO_4) and evaporated. Flash chromatography of the residue over silica gel (2.0 x 25 cm), using 0.5:99.5 EtOAc-hexane, gave **78** (174.0 mg, 79%) as a pure (^1H NMR, 300 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 3309, 2963, 2930, 2890, 2857, 2099, 1568, 1471, 1081, 823, 750 cm^{-1}; ^1H NMR (CD_2Cl_2, 300 MHz) δ 0.89 (s, 9 H), 1.04 (s, 9 H), 2.49 (d, *J* = 2.1 Hz 1 H), 3.12 (dd, *J* = 13.3, 7.1 Hz, 1 H), 3.25 (dd, *J* = 13.3, 7.1 Hz 1 H), 4.12 (s, 1H), 4.78 (ddd, *J* = 7.1, 7.1, 2.1 Hz, 1 H), 7.12 (ddd, *J* = 7.9, 7.4, 2.0 Hz, 1 H), 7.26 (ddd, *J* = 7.8, 7.4, 1.3 Hz, 1 H), 7.36 (dd, *J* = 7.8, 2.0 Hz, 1 H), 7.54 (dd, *J* = 7.9, 1.3 Hz, 1 H); ^{13}C NMR (CD_2Cl_2, 75.5 MHz) δ 19.81 (s'), 20.20 (s'), 27.25 (q'), 27.40 (q'), 45.18 (t'), 65.51 (d'), 73.90 (d'), 84.28 (s'), 125.18 (s'), 127.53 (d'), 128.89 (d'), 132.92 (d'), 133.27 (d'), 136.82 (s'); exact mass *m/z* cacld for $C_{18}H_{27}O^{79}BrSi$ 366.10150, found 366.10144.

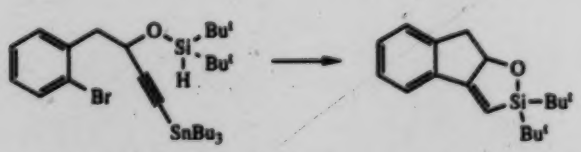
Bis(1,1-dimethylethyl)[2-[1-(2-Bromophenyl)-4-(tributylstannyl)-3-butynyl]oxy]silane (73).



78 **73**

The procedure described for **71** was followed, using **78** (120.0 mg, 0.33 mmol) in THF (1.0 mL), *n*-BuLi (0.22 mL, 1.6 M in hexanes, 0.35 mmol), an initial reaction period of 15 min, and Bu_3SnCl (0.10 mL, 0.36 mmol) in THF (0.5 mL plus 0.5 mL as a rinse). Stirring was continued at -78 °C for 30 min, and the mixture was then quenched with water (2 mL), and extracted with Et_2O (3 x 5 mL). The combined organic extracts were dried (Na_2SO_4) and evaporated to give **73** (221 mg) as a crude, colorless oil which was used directly in the next step without further purification. The compound is not stable to silica chromatography.

2,2-Bis(dimethylethyl)-8,8a-dihydro-2*H*-indeno[1,2-*d*]-1,2-oxasilole (74).



73 **74**

The procedure described for **72** was followed, using crude **73** (221 mg) in dry PhH (40 mL), Bu_3SnH (99.0 mg, 0.33 mmol) in dry PhH (5.0 mL), AIBN (54.2 mg, 0.33 mmol) in dry PhH (5.0 mL), and an addition time of 2 h. Refluxing was continued for 1 h after the addition, and the mixture was then cooled and evaporated. Flash chromatography of the residuc over silica gel (1.0 x 20 cm), using

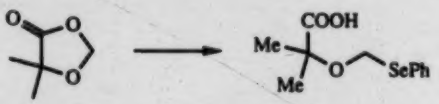
5:95 EtOAc-hexane, and rechromatography over silica gel (0.6 x 15 cm), using 3:97 EtOAc-hexane, gave **74** (55.0 mg, 58%) as a pure (^{1}H NMR, 300 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 2957, 2930, 2890, 2856, 1612, 1601, 832, 824 748 cm^{-1}; ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.00 (s, 9 H), 1.09 (s, 9 H), 2.67 (dd, *J* = 14.4, 8.2 Hz, 1 H), 3.20 (dd, *J* = 14.4, 7.7 Hz, 1 H), 5.28 (ddd, *J* = 8.2, 7.7, 2.6 Hz, 1 H), 6.02 (d, *J* = 2.6 Hz, 1 H), 7.20-7.30 (br, 3 H), 7.45-7.52 (br, 1 H); ^{13}C NMR (CD_2Cl_2, 75.5 MHz) δ 20.28 (s'), 22.26 (s'), 27.61 (q'), 28.04 (q'), 38.63 (t'), 88.67 (d'), 113.33 (d'), 122.64 (d'), 126.57 (d'), 127.62 (d'), 129.64 (d'), 136.82 (s'), 145.05 (s'), 167.67 (s'); exact mass *m/z* cacld for $C_{18}H_{26}OSi$ 286.17529, found 286.17561.

5,5-Dimethyl-1,3-dioxolan-4-one (89).[20]

88 **89**

The literature procedure was followed[20] with minor modifications. Hydroxy acid **88** (10.4 g, 100 mmol), trioxane (3.5 g, 38.5 mmol), PhH (200 mL), and *p*-TsOH·H_2O (1 g, 5.7 mmol) were stirred and refluxed for 30 h, water being removed by CaH_2 (ca. 2 g) contained in a thimble in a Soxhlet apparatus (Ar atmosphere). The reaction mixture was cooled, washed with 5% aqueous $NaHCO_3$ (20 mL), water (50 mL), and brine (20 mL) and dried (Na_2SO_4). Evaporation of the solvent, gave **89** (9.50 g, 82%) as a pure (^{1}H NMR, 300 MHz), colorless oil: ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.38 (s, 6 H), 5.35 (s, 2 H).

2-Methyl-2-[(phenylseleno)methoxy]propanoic acid (90).[16]



89 **90**

NaH (4.42 g, 60% in mineral oil, 110.6 mmol) was added in four portions to a stirred solution of PhSeSePh (19.17 g, 61.4 mmol) in THF (200 mL) (Ar atmosphere). The mixture was refluxed for 2 h and then cooled to room temperature. HMPA(8.0 mL) and then **89** (9.50 g, 81.9 mmol) in THF (10 mL plus 5.0 mL as a rinse) were injected, and the mixture was refluxed for 5 h, cooled to room temperature, and quenched with CH_3OH (30 mL). The solvent was evaporated (water pump), and water (150 mL) was added. The solution was acidified to pH ~2 with 5% aqueous $NaHSO_4$, and then extracted with Et_2O (4 x 100 mL). The combined organic extracts were washed with water (30 mL) and dried ($MgSO_4$). Evaporation of the solvent, gave crude acid **90**, which was used directly for the next step.

Methyl 2-Methyl-2-[(phenylseleno)methoxy]propanoate (91).[16]

90 **91**

MeOH (100 mL) and concentrated H_2SO_4 (10 drops) were added to all of the above crude acid. The mixture was refluxed for 10 h and cooled to room temperature. The MeOH was evaporated, and Et_2O (200 mL) was added. The mixture was washed with saturated aqueous $NaHCO_3$ (20 mL), water (20 mL), and brine (20 mL), and dried ($MgSO_4$). Evaporation of the solvent, and flash

chromatography of the residue over silica gel (4.0 x 35 cm), using 50:50 CH_2Cl_2-hexane, gave **91** (6 g, 26%) as a pure (^1H NMR, 300 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 3071, 3057, 2989, 2949, 2842, 1739, 1579, 1478, 1141, 1053 cm^{-1}; ^1H NMR (CD_2Cl_2, 300 MHz) δ 1.45 (s, 6 H), 3.66 (s, 3 H), 5.16 (s, 2 H), 7.25-7.35 (br, 3 H), 7.57-7.64 (br, 2 H); ^{13}C NMR (CD_2Cl_2, 75.5 MHz) δ 24.73 (q'), 52.35 (q'), 65.74 (t'), 79.29 (s'), 127.42 (d'), 129.34 (d'), 131.32 (s'), 132.97 (d'), 174.56 (s'); exact mass m/z cacld for $C_{12}H_{16}O_3{}^{80}Se$ 288.02646, found 288.02674.

2-Methyl-2-[(phenylseleno)methoxy]propanal (92).[16]

91 **92**

DIBAL (1.0 mL, 1.0 M in CH_2Cl_2, 1.0 mmol) was injected at a rapid dropwise rate into a stirred and cooled (-78 °C) solution of **91** (287.2 mg, 1.0 mmol) in dry CH_2Cl_2 (2.0 mL) (Ar atmosphere). Stirring at -78 °C was continued for 1 h, and the mixture was then quenched with water (5 mL). The cooling bath was removed, and stirring was continued while the mixture reached room temperature (ca. 30 min). CH_2Cl_2 (10 mL) was added, and the mixture was washed with 2% HCl (5 mL), water (5 mL), and brine (5 mL), and dried ($MgSO_4$). Evaporation of the solvent, and flash chromatography of the residue over silica gel (2.0 x 25 cm), using 50:50 CH_2Cl_2-hexane, gave **92** (213.4 mg, 83%) as a pure (^1H NMR, 200 MHz), slightly yellow oil: FTIR (CH_2Cl_2 cast) 3057, 2980, 2933, 2803, 2695, 1726, 1579, 1478, 1058, 737 cm^{-1}; ^1H NMR (CD_2Cl_2, 200 MHz) δ 1.29 (s, 6 H), 5.27 (s, 2 H), 7.25-7.34 (br, 3 H), 7.53-7.65 (br, 2 H), 9.58 (s, 1 H); ^{13}C NMR (CD_2Cl_2, 50.3 MHz) δ 21.09 (q'), 65.92 (t'), 82.18 (s'), 127.71 (d'), 129.59 (d'),

130.72 (s'), 132.97 (d'), 203.54 (d'); exact mass *m/z* cacld for $C_5H_9O_2$ (M - C_6H_5Se) 101.06026, found 101.06031.

4-Methyl-4-[(phenylseleno)methoxy]-1-trimethylsilyl-1-pentyn-3-ol (93).

92 **93**

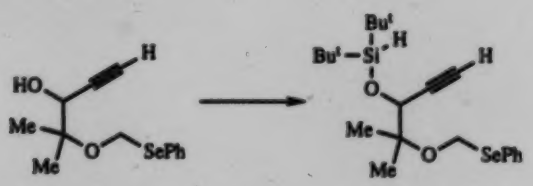
The procedure described for **69** was followed, using trimethylsilylacetylene (66.5 mg, 0.64 mmol) in THF (1.5 mL), *n*-BuLi (0.40 mL, 1.6 M in hexanes, 0.64 mmol), an initial reaction period of 20 min, and aldehyde **92** (150 mg, 0.58 mmol) in THF (0.5 mL plus 0.5 mL as a rinse). Stirring was continued at -78 °C for 30 min, and the mixture was then quenched with water (2 mL). The cooling bath was removed, and stirring was continued until the mixture had reached room temperature (ca. 30 min). The mixture was then extracted with CH_2Cl_2 (3 x 10 mL), and the combined organic extracts were dried ($MgSO_4$) and evaporated to give crude **93**, which was used directly for the next step.

4-Methyl-4-[(phenylseleno)methoxy]-1-pentyn-3-ol (94).

93 **94**

The procedure described for **68** was followed, using all the above crude **93**, dry THF (2.0 mL), and TBAF (1.5 mL, 1.0 M in THF, 1.5 mmol). The mixture was stirred at 0 °C for 2 h, and water (5 mL) was then added. The mixture was extracted with CH_2Cl_2 (3 x 10 mL), and the combined organic extracts were dried ($MgSO_4$) and evaporated. Flash chromatography of the residue over silica gel (2.0 x 20 cm), using 25:75 EtOAc-hexane, gave **94** (148.1 mg, 90%) as a pure (^{1}H NMR, 300 MHz), slightly yellow oil: FTIR (CH_2Cl_2 cast) 3451, 3290, 3071, 3056, 2979, 2936, 2872, 2118, 1579, 1478, 1064, 1054 cm^{-1}; ^{1}H NMR (CD_2Cl_2, 300 MHz) δ 1.30 (s, 3 H), 1.31 (s, 3 H), 2.49 (d, J = 2.3 Hz, 1 H), 2.64 (d, J = 5.3 Hz, 1 H), 4.25 (dd, J = 5.3, 2.3 Hz, 1 H), 5.16-5.28 (m, 2 H), 7.25-7.34 (br, 3 H), 7.57-7.65 (br, 2 H); ^{13}C NMR (CD_2Cl_2, 75.5 MHz) δ 20.40 (q'), 21.95 (q'), 65.36 (t'), 69.10 (d'), 74.30 (d'), 80.51 (s'), 82.33 (s') 127.69 (d'), 129.44 (d'), 130.84 (s'), 133.44 (d'); exact mass *m/z* cacld for $C_{13}H_{16}O_2{}^{80}Se$ 284.03156, found 284.03074.

Bis(1,1-dimethylethyl)[[1-[1-methyl-1-[(phenylseleno)methoxy]ethyl]-2-propynyl]oxy]silane (79).

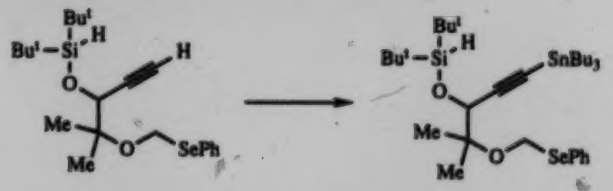


94 **79**

The procedure described for **70** was followed, using **94** (1.37 g, 4.8 mmol), imidazole (0.66 g, 9.7 mmol), *t*-Bu_2SiHCl (1.47 mL, 7.3 mmol), and THF (20 mL). The mixture was refluxed for 5 h and then cooled to room temperature. Water (10 mL) was added, and the mixture was extracted with Et_2O (3 x 20 mL).

The combined organic extracts were dried (Na_2SO_4) and evaporated. Flash chromatography of the residue over silica gel (4.5 x 30 cm), using 4:96 EtOAc-hexane, and rechromatography over silica gel (4.5 x 30 cm), using 20:80 CH_2Cl_2-hexane, gave **79** (1.85 g, 90%) as a pure (^{1}H NMR, 300 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 3309, 3072, 3058, 2965, 2931, 2890, 2857, 2108, 1580, 1470, 1097, 825 cm^{-1}; ^{1}H NMR (CD_2Cl_2, 300 MHz) δ 1.03 (s, 9 H), 1.05 (s, 9 H), 1.34 (s, 6 H), 2.49 (d, *J* = 2.1 Hz, 1 H), 4.16 (s, 1 H), 4.42 (d, *J* = 2.1 Hz, 1 H), 5.27 (d, *J* = 0.8 Hz, 2 H), 7.22-7.30 (br, 3 H), 7.58-7.66 (br, 2 H); ^{13}C NMR (CD_2Cl_2, 75.5 MHz) δ 20.06 (s'), 20.74 (s'), 21.53 (q'), 21.77 (q'), 27.62 (q'), 27.72 (q'), 64.80 (t'), 72.97 (d'), 74.81 (d'), 80.89 (s'), 82.84 (s'), 127.39 (d'), 129.35 (d'), 131.76 (s'), 133.28 (d'); exact mass *m/z* cacld for $C_{17}H_{25}O_2{}^{80}SeSi$ (M - C_4H_9) 369.07892, found 369.07977. Anal. Cacld for $C_{21}H_{34}O_2SeSi$: C, 59.27; H, 8.05. Found: C, 59.49; H, 8.10.

Bis(1,1-dimethylethyl)[[1-[1-methyl-1-[(phenylseleno)methoxy]ethyl]-3-tributylstannyl-2-propynyl]oxy]silane (80).

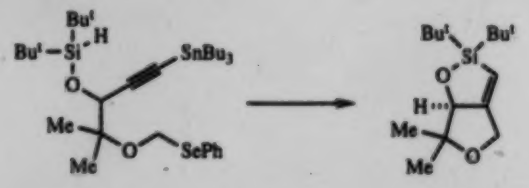


79 **80**

The procedure described for **71** was followed, using **79** (212.8 mg, 0.5 mmol) in THF (2.0 mL), *n*-BuLi (0.33 mL, 1.6 M in hexanes, 0.53 mmol), an initial reaction period of 20 min, and Bu_3SnCl (0.16 mL, 0.55 mmol) in THF (0.5 mL plus 0.5 mL as a rinse). Stirring was continued at -78 °C for 1 h, and the mixture was then quenched with water (2 mL), and extracted with Et_2O (3 x 10 mL). The

combined organic extracts were dried (Na_2SO_4) and evaporated to give **80** (370 mg) as a crude colorless oil, which was used directly in the next step without further purification. The compound is not stable to silica chromatography.

2,2-Bis(1,1-dimethylethyl)-2,4,6,6b-tetrahydro-6,6-dimethyl-furo[3,4-*d*]-1,2-oxasilole (81).



80 **81**

The procedure described for **72** was followed, using crude **80** (370 mg) in dry PhH (50 mL), Bu_3SnH (0.14 mL, 0.5 mmol) in dry PhH (7.0 mL), AIBN (82.1 mg, 0.5 mmol) in dry PhH (7.0 mL), and an addition time of 2 h. Refluxing was continued for 2 h after the addition, and the mixture was then cooled and evaporated. Flash chromatography of the residue over silica gel (1.0 x 20 cm), using 7:95 EtOAc-hexane, and again over silica gel (0.6 x 15 cm), using 3:93 EtOAc-hexane, gave **81** (108 mg, 81%) as a pure (^{1}H NMR, 400 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 3032, 2971, 2932, 2894, 2858, 1620, 1474, 1092, 824 cm^{-1}; ^{1}H NMR (CD_2Cl_2, 400 MHz) δ 0.97 (s, 3 H), 1.03 (s, 9 H), 1.04 (s, 9 H), 1.33 (s, 3 H), 4.18-4.25 (m, 1 H), 4.35-4.45 (m, 1 H), 4.58-4.62 (m, 1 H), 5.80-5.83 (m, 1 H); ^{13}C NMR (CD_2Cl_2, 100.6 MHz) δ 20.16 (q'), 21.08 (s'), 22.69 (s'), 26.82 (q'), 27.43 (q'), 28.22 (q'), 64.77 (t'), 79.57 (s'), 92.44 (d'), 115.60 (d'), 167.34 (s'); exact mass *m/z* calcd for $C_{14}H_{25}O_2Si$ (M - CH_3) 253.16238, found 253.16268. Anal. Calcd for $C_{15}H_{28}O_2Si$: C, 67.11; H, 10.51. Found: C, 67.09; H, 10.62.

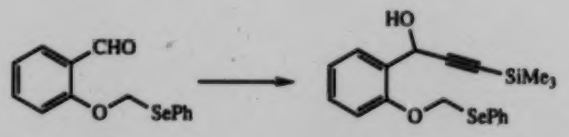
2-[(Phenylseleno)methoxy]benzaldehyde (96).[16]

95 **96**

Dry acetone (20 mL) was added to $PhSeCH_2Cl$ (3.16 g, 15.4 mmol) and NaI (11.52 g, 76.9 mmol), and the mixture was refluxed for 3 h, cooled to room temperature, and concentrated. The solid was filtered off, and washed with Et_2O (20 mL). The combined washings were evaporated to give crude $PhSeCH_2I$, which was used directly for the next step.

Salicyl aldehyde **95** (1.22 g, 10.0 mmol) in THF (2.0 mL) was added by cannula to a stirred suspension of NaH (0.45 g, 60% in mineral oil, 12 mmol) in THF at 0 °C over ca. 1 min. The mixture was stirred at 0 °C for 20 min, and then a solution of $PhSeCH_2I$ in THF (5 mL) was added by cannula over ca. 1 min. The mixture was refluxed for 4 h, and then cooled to room temperature. Water (10 mL) was added, and the mixture was extracted with CH_2Cl_2 (3 x 10 mL). The combined organic extracts were dried (Na_2SO_4) and evaporated. Flash chromatography of the residue over silica gel (3 x 25 cm), using increasing amounts of EtOAc in hexane (from 5% to 15%), gave **96** (650 mg, 22%) as a pure (^1H NMR, 300 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 3072, 3057, 2859, 2759, 1689, 1598, 1579, 1479, 1202 cm^{-1}; ^1H NMR (CD_2Cl_2, 300 MHz) δ 5.82 (s, 2 H), 7.05 (d, J = 8.3 Hz, 1 H), 7.13 (dd, J = 7.7, 7.7 Hz, 1 H), 7.26-7.35 (br, 3 H), 7.53-7.63 (m, 3 H), 7.82 (dd, J = 7.7, 1.8 Hz, 1 H), 10.34 (d, J = 0.89 Hz, 1 H); ^{13}C NMR (CD_2Cl_2, 75.5 MHz) δ 68.60 (t'), 114.84 (d'), 122.43 (d'), 126.72 (s'), 128.29 (d'), 128.72 (d'), 129.03 (s'), 129.71 (d'), 133.84 (d'), 135.85 (d'), 159.55 (s'), 189.47 (d'); exact mass *m/z* cacld for $C_{14}H_{12}O_2{}^{80}Se$ 292.00024, found 292.00048.

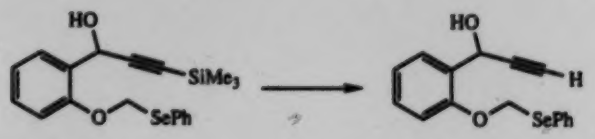
1-[2-[(Phenylseleno)methoxy]phenyl]-3-trimethylsilyl-2-propyn-1-ol (97).



96 **97**

The procedure described for **69** was followed, using trimethylsilylacetylene (229.4 mg, 2.2 mmol) in THF (4 mL), *n*-BuLi (1.38 mL, 1.6 M in hexanes, 2.2 mmol), an initial reaction period of 15 min, and aldehyde **96** (534 mg, 1.8 mmol) in THF (1.0 mL plus 1.0 mL as a rinse). Stirring was continued at -78 °C for 1 h. The cooling bath was removed, and stirring was continued until the mixture had reached room temperature (ca. 30 min). The mixture was then quenched with saturated aqueous NH_4Cl (1 mL). Water (2 mL) was added and the mixture was extracted with CH_2Cl_2 (3 x 10 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated to give crude **97**, which was used directly for the next step.

1-[2-[(Phenylseleno)methoxy]phenyl]-2-propyn-1-ol (98).

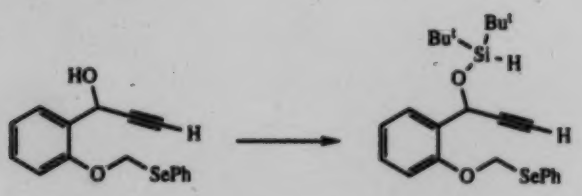


97 **98**

The procedure described for **68** was followed, using crude **97**, dry THF (5 mL), and TBAF (3.6 mL, 1.0 M in THF, 3.6 mmol). The mixture was stirred at 0 °C for 30 min. Water (5 mL) was then added, and the mixture was extracted with CH_2Cl_2 (3 x 10 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated. Flash chromatography of the residue over silica gel (3 x 20 cm), using 1:20:20 EtOAc-CH_2Cl_2-hexane, gave **98** (520 mg, 91%) as a pure (^{1}H NMR, 300

MHz), white solid: mp 98-99 °C; FTIR (microscope) 3293, 3268, 3076, 3061, 2110, 1602, 1589, 1208, 1021, 741 cm^{-1}; ^1H NMR (CD_2Cl_2, 300 MHz) δ 2.61 (d, J = 2.2 Hz, 1 H), 2.70 (d, J = 6.2 Hz, 1 H), 5.62 (dd, J = 6.2, 2.2 Hz, 1 H), 5.78 (s, 2 H), 6.97 (dd, J = 8.2, 0.9 Hz, 1 H), 7.08 (ddd, J = 7.6, 7.6, 1.0 Hz, 1 H), 7.26-7.36 (br, 4 H), 7.55-7.65 (br, 3 H); ^{13}C NMR (CD_2Cl_2, 75.5 MHz) δ 60.59 (d'), 68.42 (t'), 74.29 (d'), 83.48 (s'), 113.76 (d'), 122.54 (d'), 128.25 (d'), 128.41 (d'), 129.68 (d'), 129.83 (s'), 129.57 (d'), 130.31 (s'), 133.93 (d'), 154.41 (s'); exact mass *m/z* cacld for $C_{16}H_{14}O_2{}^{80}Se$ 318.01590, found 318.01506.

Bis(1,1-dimethylethyl)[[1-[2-[(phenylseleno)methoxy]phenyl]-2-propynyl]oxy]silane (82).

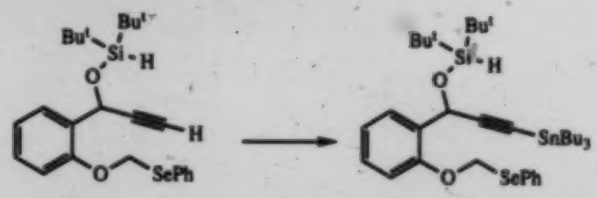


98 **82**

The procedure described for **70** was followed, using **98** (460 mg, 1.4 mmol), imidazole (190.6 mg, 2.8 mmol), *t*-Bu_2SiHCl (0.44 mL, 2.2 mmol), and THF (20 mL). The mixture was refluxed for 6 h and then cooled to room temperature. Water (10 mL) was added, and the mixture was extracted with Et_2O (3 x 20 mL). The combined organic extracts were dried (Na_2SO_4) and evaporated. Flash chromatography of the residue over silica gel (3 x 20 cm), using 2:98 EtOAc-hexane, gave **82** (592 mg, 92%) as a pure (^1H NMR, 200 MHz), yellowish oil: FTIR (CH_2Cl_2 cast) 3307, 3073, 3060, 2998, 1601, 1591, 1580, 1205, 826 cm^{-1}; ^1H NMR (CD_2Cl_2, 200 MHz) δ 0.89 (s, 9 H), 1.08 (s, 9 H), 2.50 (d, J = 2.1 Hz, 1 H), 4.11 (s, 1 H), 5.76 (s, 2 H), 5.81 (d, J = 2.1 Hz, 1 H), 6.90 (dd, J = 8.1, 0.7

Hz, 1 H), 7.07 (ddd, J = 7.4, 7.4 0.9 Hz, 1 H), 7.20-7.35 (br, 4 H), 7.55-7.72 (br, 3 H); ^{13}C NMR (CD_2Cl_2, 50.3 MHz) δ 20.02 (s'), 20.25 (s'), 27.22 (q'), 27.41 (q'), 62.40 (d'), 68.34 (t'), 73.14 (d'), 84.57 (s'), 113.23 (d'), 122.41 (d'), 127.97 (d'), 128.08 (d'), 129.22 (d'), 129.58 (d'), 130.43 (s'), 131.46 (s'), 133.66 (d'), 153.25 (s'); exact mass *m/z* cacld for $C_{18}H_{27}O_2Si$ (M - C_6H_5Se) 303.17804, found 303.17712. Anal. Cacld for $C_{24}H_{32}O_2SeSi$: C, 62.72; H, 7.02. Found: C, 62.44; H, 6.97.

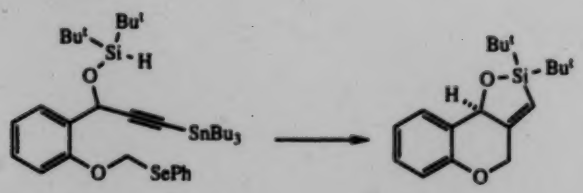
Bis(1,1-dimethylethyl)[[1-[2-[(phenylseleno)methoxy]phenyl]-3-tributylstannyl-2-propynyl]oxy]silane (83).



82 **83**

The procedure described for **71** was followed, using **82** (185.0 mg, 0.40 mmol) in THF (1.5 mL), *n*-BuLi (0.26 mL, 1.6 M in hexanes, 0.42 mmol), an initial reaction period of 15 min, and Bu_3SnCl (0.13 mL, 0.44 mmol) in THF (0.5 mL plus 0.5 mL as a rinse). Stirring was continued at -78 °C for 30 min, and the mixture was then quenched with water (2 mL), and extracted with Et_2O (3 x 5 mL). The combined organic extracts were dried (Na_2SO_4) and evaporated, to give **83** (310 mg) as a crude colorless oil, which was used directly in the next step without further purification. The compound is not stable to silica chromatography.

2,2-Bis(1,1-dimethylethyl)-2,9b-dihydro-4*H*-1,2-oxasilolo[4,5-*c*][1]benzopyran (84).



83 **84**

The procedure described for **72** was followed, using crude **83** (310 mg) in dry PhH (40 mL), Bu_3SnH (0.11 mL, 0.40 mmol) in dry PhH (6.0 mL), AIBN (65.7 mg, 0.40 mmol) in dry PhH (6.0 mL), and an addition time of 2 h. Refluxing was continued for 7 h after the addition, and the mixture was then cooled and evaporated. Flash chromatography of the residue over silica gel (2.0 x 25 cm), using 3:97 EtOAc-hexane, and again over silica gel (1.0 x 20 cm), using 30:70 CH_2Cl_2-hexane, gave **84** (85.0 mg, 70%) as a pure (^{1}H NMR, 300 MHz), white solid: mp 80.5 °C-81.5 °C; FTIR (CH_2Cl_2 cast) 3074, 3037, 1610, 1582, 1055, 824 cm^{-1}; ^{1}H NMR (CD_2Cl_2, 300 MHz) δ 0.88 (s, 9 H), 1.08 (s, 9 H), 4.78-4.94 (m, 2 H), 5.60-5.66 (br, 1 H), 5.90-5.96 (m, 1 H), 6.79 (dd, *J* = 8.1, 1.2 Hz, 1 H), 6.95 (ddd, *J* = 7.4, 7.4, 1.2 Hz, 1 H), 7.10-7.18 (m, 1 H), 742-7.50 (m, 1 H); ^{13}C NMR (CD_2Cl_2, 75.5 MHz) δ 20.23 (s'), 21.58 (s'), 27.45 (q'), 27.65 (q'), 68.55 (t'), 78.46 (d'), 116.39 (d'), 118.94 (d'), 121.24 (d'), 126.39 (d'), 128.27 (s'), 128.56 (d'), 153.47 (s'), 156.45 (s'); exact mass *m/z* cacld for $C_{18}H_{26}O_2Si$ 302.17020, found 302.16948.

***N*-[(1,1-Dimethylethoxy)carbonyl]-*N*-[(phenylseleno)methyl]glycine (100).**[16]

99 **100**

The procedure described for **90** was followed, using PhSeSePh (671 mg, 2.15 mmol), THF (10 mL), NaH (116 mg, 80% in mineral oil, 3.87 mmol), a reflux period of 2 h, HMPA (0.5 mL), and **99**[23] (536 mg, 2.87 mmol) in THF (1.0 mL plus 1.0 mL as a rinse). The mixture was refluxed for 5 h, and then quenched with CH_3OH (2 mL). The solvent was evaporated, and water (10 mL) was added. The solution was acidified to pH~2 with 5% aqueous $NaHSO_4$, and then extracted with Et_2O (5 x 10 mL). The combined organic extracts were washed with water (10 mL) and dried ($MgSO_4$). Evaporation of the solvent, gave crude acid **100**, which was used directly for the next step.

Methyl *N*-[(1,1-Dimethylethoxy)carbonyl]-*N*-[(phenylseleno)methyl]-glycinate (101).[16]

100 **101**

DBU (0.43 mL, 2.87 mmol) and CH_3I (0.54 mL, 8.61 mmol) were injected into a stirred solution of crude acid **100** in THF (10 mL), and the mixture was stirred at room temperature for 12 h (Ar atmosphere). The precipitate was filtered off and washed with Et_2O (10 mL). Evaporation of the filtrate, and flash

chromatography of the residue over silica gel (3.0 x 25 cm), using 15:85 EtOAc-hexane, gave **101** (640 mg, 62%) as a pure (^{1}H NMR, 300 MHz), yellowish oil: FTIR (CH_2Cl_2 cast) 3071, 3056, 2976, 2953, 2932, 2875, 1753, 1704, 1579, 1477, 1229, 1157 cm^{-1}; ^{1}H NMR (CD_2Cl_2, 300 MHz) δ 1.25 and 1.32 (two s, 9 H), 3.70 (s, 3 H), 3.92 and 4.12 (two s, 2 H), 4.88 and 4.92 (two s, 2 H), 7.20-7.35 (br, 3 H), 7.52-7.65 (br, 2 H); ^{13}C NMR (CD_2Cl_2, 75.5 MHz) δ 28.05 (q'), 28.15 (q'), 47.26 (t'), 47.48 (t'), 47.92 (t'), 48.51 (t'), 52.27 (q'), 81.37 (s'), 128.01 (d'), 128.39 (d'), 128.86 (s'), 129.12 (s'), 129.40 (d'), 129.48 (d'), 134.88 (d'), 135.82 (d'), 154.25 (s'), 154.42 (s'), 170.12 (s'), 170.16 (s'); exact mass (HRES) *m/z* cacld for $C_{15}H_{22}NO_4{}^{80}Se$ (M + H) 360.071404, found 360.072560.

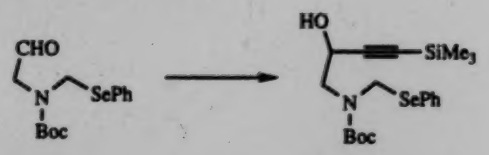
***N*-[(1,1-Dimethylethoxy)carbonyl]-*N*-[(phenylseleno)methyl]glycinal (102).**[16]

101 **102**

The procedure described for **92** was followed, using **101** (370 mg, 1.03 mmol), dry CH_2Cl_2 (2.0 mL), and DIBAL (1.24 mL, 1.0 M in CH_2Cl_2, 1.24 mmol). The mixture was stirred at -78 °C for 1 h, and then quenched with water (1 mL). The cooling bath was removed, the mixture was stirred for 10 min, and then filtered through a pad of Celite, which was washed with Et_2O (20 mL). The filtrate was dried ($MgSO_4$) and evaporated. Flash chromatography of the residue over silica gel (3.0 x 20 cm), using 12:88 EtOAc-hexane, gave **102** (279 mg, 83%) as a pure (^{1}H NMR, 400 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 3071, 3057, 2977, 2931, 2872, 2819, 2720, 1735, 1698, 1579, 1477, 1158 cm^{-1}; ^{1}H NMR (CD_2Cl_2, 400 MHz) δ 1.26 and 1.34 (two s, 9 H), 3.86 and 3.98 (two s, 2 H), 4.90 and 4.95 (two

s, 2 H), 7.21-7.39 (br, 3 H), 7.55-7.65 (br, 2 H), 9.45 and 9.50 (two s, 1 H); ^{13}C NMR (CD_2Cl_2, 100.6 MHz) δ 28.00 (q'), 28.11 (q'), 47.89 (t'), 48.48 (t'), 56.56 (t'), 57.15 (t'), 81.63 (s'), 81.80 (s'), 128.14 (d'), 128.51 (d'), 128.59 (s'), 128.73 (s'), 129.51 (d'), 129.58 (d'), 134.89 (d'), 135.79 (d'), 154.23 (s'), 154.71 (s'), 198.45 (d'), 198.51 (d') ; exact mass (HRES) *m/z* cacld for $C_{14}H_{20}NO_3{}^{80}Se$ (M + H) 330.060839, found 330.059420.

1,1-Dimethylethyl (2-hydroxy-4-trimethylsilyl-3-butynyl)[(phenyl-seleno)methyl]carbamate (103).



102 **103**

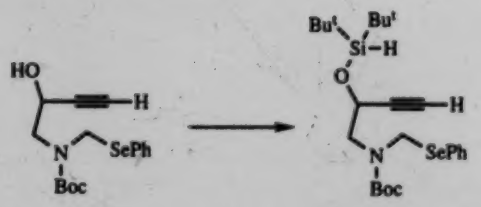
The procedure described for **69** was followed, using trimethylsilylacetylene (100.3 mg, 0.96 mmol) in THF (2.0 mL), *n*-BuLi (0.51 mL, 1.6 M in hexanes, 0.81 mmol), an initial reaction period of 15 min, and aldehyde **102** (243 mg, 0.74 mmol) in THF (1.0 mL plus 0.5 mL as a rinse). Stirring was continued at -78 °C for 1 h. The cooling bath was removed, stirring was continued until the mixture had 0 °C (ca. 30 min), and the mixture was quenched with saturated aqueous NH_4Cl. Water (2 mL) was added, and the mixture was extracted with CH_2Cl_2 (3 x 10 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated to give crude **103**, which was used directly for the next step.

1,1-Dimethylethyl (2-hydroxy-3-butynyl)[(phenylseleno)methyl]-carbamate (104).

103 **104**

The procedure described for **68** was followed, using crude **103**, dry THF (2 mL), and TBAF (1.1 mL, 1.0 M in THF, 1.1 mmol). The mixture was stirred at 0 °C for 2 h. Water (2 mL) was added, and the mixture was extracted with CH_2Cl_2 (3 x 5 mL). The combined organic extracts were dried ($MgSO_4$) and evaporated. Flash chromatography of the residue over silica gel (2.0 x 25 cm), using 20:80 EtOAc-hexane, gave **104** (237 mg, 90%) as a pure (^1H NMR, 300 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 3424, 3295, 3071, 3056, 2977, 2932, 2116, 1697, 1677, 1579, 1157 cm^{-1}; ^1H NMR (CH_2Cl_2, 400 MHz) δ 1.24 and 1.38 (two s, 9 H), 2.50 and 2.86 (two s, 1 H), 3.42-3.80 (m, 3 H), 4.54 (br, 1 H), 4.80-5.04 (m, 2H), 7.21-7.41 (br, 3 H), 7.58-7.64 (br, 2 H); ^{13}C NMR (CD_2Cl_2, 100.6 MHz, -40 °C) δ 27.31 (q'), 27.70 (q'), 47.81 (t'), 48.28 (t'), 51.47 (t'), 51.65 (t'), 60.27 (d'), 60.64 (d'), 73.56 (d'), 73.76 (d'), 80.80 (s'), 81.15 (s'), 82.70 (s'), 82.74 (s'), 127.49 (s'), 127.75 (d'), 127.85 (s'), 128.25 (d'), 128.91 (d'), 129.07 (d'), 135.17 (d'), 136.13 (d'), 154.15 (s'), 155.64 (s'); exact mass (HRES) *m/z* cacld for $C_{16}H_{21}NNaO_3{}^{80}Se$ (M + Na) 378.058434, found 378.059140.

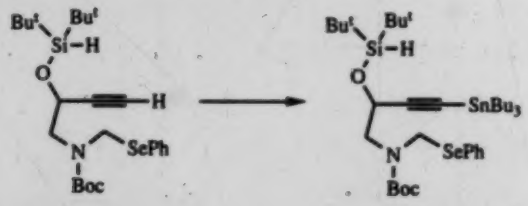
1,1-Dimethylethyl [2-[[bis(1,1-dimethylethyl)silyl]oxy]-3-butynyl]-[(phenylseleno)methyl]carbamate (85).



104 **85**

The procedure described for **70** was followed, using **104** (225 mg, 0.64 mmol), imidazole (86.5 mg, 1.27 mmol), *t*-Bu_2SiHCl (0.19 mL, 0.96 mmol), and THF (3.0 mL). The mixture was refluxed for 3 h and then cooled to room temperature. Water (5 mL) was added, and the mixture was extracted with Et_2O (3 x 10 mL). The combined organic extracts were dried (Na_2SO_4) and evaporated. Flash chromatography of the residue over silica gel (2.0 x 25 cm), using 5:95 EtOAc-hexane, gave **85** (281 mg, 88%) as a pure (^1H NMR, 300 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 3310, 3253, 2964, 2931, 2891, 2857, 2103, 1702, 1579, 1471, 1159, 826 cm^{-1}; ^1H NMR (CH_2Cl_2, 300 MHz) δ 0.95 (s, 9 H), 1.01 (s, 9 H), 1.25-1.36 (two s, 9 H), 2.49 (d, J = 0.7 Hz, 1 H), 3.36-3.52 (br, 2 H), 4.08 (s, 1 H), 4.55-4.75 (m, 1 H), 4.75-5.14 (m, 2 H), 7.19-7.34 (br, 3 H), 7.55-7.65 (br, 2 H); ^{13}C NMR (CD_2Cl_2, 100.6 MHz, -40 °C) δ 19.37 (s'), 19.48 (s'), 20.07 (s'), 20.24 (s'), 26.78 (q'), 26.94 (q'), 26.99 (q'), 27.61 (q'), 27.95 (q'), 48.28 (t'), 49.09 (t'), 51.91 (t'), 52.10 (t'), 64.24 (d'), 64.63 (d'), 74.04 (s'), 74.14 (s'), 80.35 (d'), 80.73 (d'), 82.58 (s'), 82.70 (s'), 127.79 (s'), 128.09 (s'), 128.20 (d'), 128.48 (s'), 129.08 (d'), 129.16 (d'), 135.12 (d'), 136.16 (d'), 154.04 (s'), several of peaks must coincide; exact mass (HRES) *m/z* cacld for $C_{24}H_{39}NNaO_3{}^{80}SeSi$ (M + Na) 520.176213, found 520.174600.

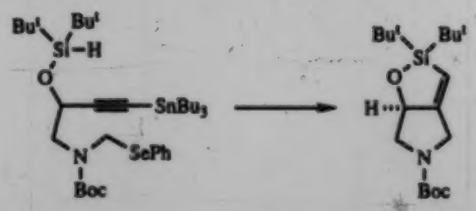
1,1-Dimethylethyl [2-[[bis(1,1-dimethylethyl)silyl]oxy]-4-tributyl-stannyl-3-butynyl][(phenylseleno)methyl]carbamate (86).



85 **86**

The procedure described for **71** was followed, using **85** (100.0 mg, 0.20 mmol) in THF (1.0 mL), *n*-BuLi (0.14 mL, 1.6 M in hexanes, 0.22 mmol), an initial reaction period of 15 min, and Bu_3SnCl (81.4 mg, 0.24 mmol) in THF (0.5 mL plus 0.5 mL as a rinse). Stirring was continued at -78 °C for 30 min, and the mixture was then quenched with water (2 mL), and extracted with Et_2O (3 x 5 mL). The combined organic extracts were dried (Na_2SO_4) and evaporated, to give crude **86** (151 mg) as a colorless oil, which was used directly in the next step without further purification. The compound is not stable to silica chromatography.

1,1-Dimethylethyl 2,2-bis(1,1-dimethylethyl)-2,4,6,6a-tetrahydro-5*H*-1,2-oxasilolo[4,5-*c*]pyrrole-5-carboxylate (87).



86 **87**

The procedure described for **72** was followed, using crude **86** (151 mg) in dry PhH (20 mL), Bu_3SnH (60.0 mg, 0.20 mmol) in dry PhH (3.0 mL), AIBN (32.8 mg, 0.20 mmol) in dry PhH (3.0 mL), and an addition period of 2 h.

Refluxing was continued for 1 h after the addition, and the mixture was then cooled and evaporated. Flash chromatography of the residue over silica gel (1 x 20 cm), using 10:90 EtOAc-hexane, and rechromatography over silica gel (0.6 x 15 cm), using 5:95 EtOAc-hexane, gave **87** (48.0 mg, 71%) as a pure (^{1}H NMR, 400 MHz), colorless oil: FTIR (CH_2Cl_2 cast) 2960, 2931, 2858, 1704, 1629, 1473, 1158, 1103, 823 cm^{-1}; ^{1}H NMR (CD_2Cl_2, 400 MHz) δ 0.99 (s, 9 H), 1.02 (s, 9 H), 1.42 (s, 9 H), 2.70-2.80 (br, m, 1 H), 3.85-4.03 (br, m, 3 H), 4.95 (br, m, 1 H), 5.86 (br, s, 1 H); ^{13}C NMR (CD_2Cl_2, 50.3 MHz) δ 20.20 (s'), 21.79 (s'), 27.04 (q'), 27.34 (q'), 27.71 (q'), 28.51 (q'), 46.78 (t'), 47.30 (t'), 50.46 (t'), 51.33 (t'), 79.60 (s'), 83.00 (d'), 83.40 (d'), 116.92 (d'), 117.08 (d'), 154.62 (s'), 154.83 (s'), 162.47 (s'), 163.03 (s'), several of peaks must coincide; exact mass (HRES) m/z cacld for $C_{18}H_{34}NO_3Si$ (M + H) 340.230798, found 340.231100.

V. REFERENCES AND FOOTNOTES

1. Baldwin, J. E. *J. Chem. Soc. Chem. Commun.* **1976**, 734.

2. Beckwith, A. L. J.; Easton, C. J.; Serelis, A.K. *J. Chem. Soc. Chem. Commun.* **1980**, 482.

3. Gilbert, B. C.; Parry, D. J. *J. Chem. Soc., Perkin. Trans. 2*, **1986**, 1345.

4. Gilbert, B. C.; Parry, D. J. *J. Chem. Soc., Perkin. Trans. 2*, **1988**, 875.

5. Gopalsamy, A.; Balasubramanian, K. K. *J. Chem. Soc., Chem. Commun.* **1988**, 28.

6. Rao, A. V. R.; Singh, A. K.; Rao, B. V.; Reddy, K. M. *Tetrahedron Lett.* **1993**, *34*, 2665.

7. Ishibashi, H.; Nakamura, N.; Sato, T.; Takeuchi, M.; Ikeda, M. *Tetrahedron Lett.* **1991**, *32*, 1725.

8. Sato, T.; Nakamura, N.; Ikeda, K.; Okada, M.; Ishibashi, H.; Ikeda, M. *J. Chem. Soc., Perkin. Trans. 1*, **1992**, 2399.

9. Sato, T.; Chono, N.; Ishibashi, H.; Ikeda, M. *J. Chem. Soc., Perkin. Trans. 1*, **1995**, 1115.

10. Goodall, K.; Parsons, A. F. *J. Chem. Soc., Perkin. Trans. 1*, **1994**, 3257.

11. Bogen, S.; Malacria, M. *J. Am. Chem. Soc.* **1996**, *118*, 3992.

12. Barton, T. J.; Revis, A. *J. Am. Chem. Soc.* **1984**, *106*, 3802.

13. Chatgilialoglu, C.; Woynar, H.; Ingold, K. U.; Davies, A. G. *J. Chem. Soc., Perkin. Trans. 2*, **1983**, 555.

14. Baldwin, J. E.; Cutting, J.; Dupont, W.; Kruse, L.; Silberman, L.; Thomas, R. C. *J. Chem. Soc., Chem. Commun.* **1976**, 736.

15. Clive, D. L. J.; Cantin, M. *J. Chem. Soc., Chem. Commun.* **1995**, 319.

16. Clive, D. L. J.; Yang, W. *J. Chem. Soc., Chem. Commun.* **1996**, 1605.

17. Langkopf, E.; Schinzer, D. *Chem. Rev.* **1995**, *95*, 1375.

18. Bergstra, R, J. Ph.D. Thesis, University of Alberta, 1991.

19. Suzuki, M.; Kimura, Y.; Terashima, S. *Chem. Lett.* **1984**, 1543.

20. Farines, M.; Soulier, J. *Bull. Soc. Chim. Fr.* **1970**, 332.

21. (a) Dowd, P.; Kennedy, P. Synth. Commun. 1981, 11, 935. (b) Scarborough Jr, R. M.; Smith III, A. B. *Tetrahedron Lett.* **1977**, 4361. (c) Liotta, D.; Santiestaban, H. *Tetrahedron Lett.* **1977**, 4369. (d) Ley, S. V.; O'Neil, I. A.; Low, C. M. R. *Tetrahedron* **1986**, *42*, 5363.

22. Hartman, G. D.; Phillips, B. T.; Halczenko, W. *J. Org. Chem.* **1985**, *50*, 2423.

23. Walter, M. W.; Adlington, R. M.; Baldwin, J. E.; Chuhan, J.; Schofield, C. J. *Tetrahedron Lett.* **1995**, *36*, 7761.